

BASIN ANALYSIS AND HYDROCARBON POTENTIAL OF THE PAPUAN BASIN,

A FRONTIER BASIN IN PAPUA NEW GUINEA

A THESIS

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BY

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Table of Contents

List of Figures	4
List of Tables	6
List of Appendices	7
Abstract	9
Introduction	11
Geologic Background	14
<i>Exploration History</i>	14
<i>Depositional Megasequences</i>	16
<i>Tectonics of the Papuan Basin</i>	21
<i>Lithology</i>	25
<i>Stratigraphy</i>	28
<i>Possible Source Rocks</i>	31
<i>Possible Reservoir Rocks</i>	31
Methods	32
<i>Data Collection</i>	32
<i>Data Preparation</i>	32
<i>Database Construction and Utilization</i>	33
Results	35
<i>Jurassic and Cretaceous Sourced Interval</i>	40
<i>Miocene Carbonate Sourcing</i>	55
<i>Structural Cross Section's</i>	58
<i>Gulf of Papua Extensional Faulting and Reef Structures</i>	75

Discussion	77
<i>Hydrocarbon Trap Modeling: Structural Cross-Section's and PETRA Modeling</i>	79
<i>Jurassic Sourced Rift Play</i>	80
<i>Jurassic Sourced Thrust Play</i>	82
<i>Tertiary Gas-Condensate Play</i>	86
 Conclusion	 89
 Future Work	 90
 References	 91
 Appendix	 96

LIST OF FIGURES

Figure 1: Satellite imagery of Papua New Guinea	12
Figure 2: Outline of the Papuan Basin and the Shelf Platform	13
Figure 3: Location of recently targeted hydrocarbon plays	15
Figure 4: Generalized depositional megasequence summary for the Western Papuan Basin	17
Figure 5: Geologic-cross section across part of the Papuan Basin	22
Figure 6: Location map of various tectonic and structural features	24
Figure 7: Regional Stratigraphic Column for the Papuan Basin	26
Figure 8: Map of Papua New Guinea	34
Figure 9: Structural map of Papua New Guinea	35
Figure 10: Interpreted fault locations in reference to the Jurassic-Cretaceous units	36
Figure 11: Constructed basement grid map	37
Figure 12: A 3D model of the Basement rock in the Papuan Basin	38
Figure 13: 3D structural model of the Magobu Formation	40
Figure 14: Constructed grid map of the Magobu Formation	41
Figure 15: 3D structural model of the Middle Jurassic Barikewa Formation	42
Figure 16: Structural contour map of the Barikewa Formation	43
Figure 17: 3D structural model of the Koi-Iange Formation	44
Figure 18: Structural contour map of the Koi-Iange Formation	45
Figure 19: Contoured isopach map of the Imburu Formation	46
Figure 20: 3D model of the Jurassic Imburu Mudstone	47
Figure 21: Structural contour map of the Jurassic Imburu Formation	48
Figure 22: Contoured isopach map of the Jurassic Toro Sandstone	49
Figure 23: 3D contour map of the Jurassic Toro Sandstone	50
Figure 24: Structural contour map of the Jurassic Toro Sandstone	51
Figure 25: 3D model of the Jurassic Ieru Formation	52
Figure 26: Structural contour map of the Jurassic Ieru Formation	53

Figure 27: 3D model of the Miocene Darai Limestone	55
Figure 28: Contoured map of the Miocene Darai Limestone	56
Figure 29: Structural subsurface cross section between the wells Iehi – Barikewa – Omati 1	58
Figure 30: Structural subsea cross section between the wells Kanau – Iehi – Orie	60
Figure 31: Cross section between Kiunga – Lake Murray 1 – Lake Murray 2 – and Morehead	62
Figure 32: Structural cross section between Orie – Dara – Aramia	64
Figure 33: Structural cross section between Darai and Barikewa	66
Figure 34: Structural cross section between Komewu 2 – Omati 1 – and Muabu	68
Figure 35: Structural cross section between Kiunga – Mananda – Iehi – Bwata	69
Figure 36: Structural cross section between Mananda – Kanau – Darai	70
Figure 37: Structural cross section between Barikewa – Uramu – Puri – Pasca A1	71
Figure 38: Structural cross section between Muabu – Uramu - Dibiri	72
Figure 39: Structural cross section between Morehead – Mutare – Wuroi - Kusa	73
Figure 40: 1979 reprocessed seismic line of the Pasca A3 well	74
Figure 41: Normal faults extending into the offshore Gulf of Papua	75
Figure 42: Diagram of Fault Block Rotation	82

LIST OF TABLES

Table 1: Well symbols used within the Petra database	32
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LIST OF APPENDICIES

Appendix A: <i>Dry Hole Analysis</i>	95
Appendix B: Chart of well locations and well type	99
Appendix C: Well production amounts	100
Appendix D: Additional 3D Modeling of Jurassic units	101
Appendix E: Contoured grid maps of additional formations in the Papuan Basin	104

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ABSTRACT

The Papuan Basin is a lightly explored foreland basin on the Western portion of the island of Papua New Guinea. The Papuan Basin consists of several drilled wells on both the onshore and offshore portions of the basin. Presently, the Papuan Basin is considered a frontier basin due to the presence of many dry exploration wells. Some of these wells have limited production, while most are dry holes. Limited seismic control, combined with a structurally complex basin and poor infrastructure, have hindered current exploration activities. This study attempts to understand why the Papuan Basin is still considered a frontier basin, and address the hydrocarbon potential of the basin. Existing log data will be used to better comprehend the Geologic processes surrounding hydrocarbon generation and reservoir formation. Advances in modern modeling software has allowed for new stratigraphic and structural correlations to be made across the basin, which will ultimately lead to new hydrocarbon discoveries.

Currently, we interpret two major hydrocarbon producing sources within the Papuan Basin. These consist of the Jurassic Imburu Formation, and Miocene carbonates such as the Yala and Darai limestones. Cretaceous sandstones, such as the Toro, provide excellent reservoir rocks for migrated hydrocarbons that are ultimately sealed by interbedded shales and the Cretaceous Ieru Formation. Our investigation suggests that maturation of organic material took place within large grabens and basement lows at depths greater than 2000 meters in the central part of the onshore Papuan Basin. Jurassic units within grabens have plunged deep enough to enter the zone for thermal maturation of hydrocarbons. Hydrocarbons would have migrated up fault planes into structural and stratigraphic traps. However, the timing of oil migration throughout the basin is poorly understood due to the basins complex structural history. Ideal structural traps are located within anticlinal structures on the upthrown blocks of reverse faults. These anticlinal structures

developed because of fault wedge rotation. The Antelope and Gobe fields are model fields for this petroleum system. The offshore Papuan Basin shelf platform is dominated by a productive Miocene carbonate reef system that extends into the Gulf of Papua.

Outside of these two production zones, formations in the Jurassic are relatively unproductive at depths shallower than 2000 meters. Further seismic exploration and well log data will need to be gathered in order to analyze the stratigraphic gaps between numerous wells. Locations around basement lows and grabens are plausible exploration zones for future well development.

INTRODUCTION

Statement of Problem

The Papuan Basin has been considered a frontier basin since the early 1960's, and scientists have been unable to explain the lack of hydrocarbon productivity. While oil and gas wells are abundant in the Papuan Fold Belt to the Northeast, there has been limited success in the Papuan foreland basin. Unprofitable oil and gas prices have halted current exploration projects in the region. Scientists believe the Papuan Basin might contain large unexplored oil and gas reserves. However, there is a limited understanding of the petroleum systems in the Papuan Basin.

The Papuan Basin is a lightly explored foreland basin on the island of Papua New Guinea. The area consists of 52 conventionally drilled wells on the onshore and offshore portions of the basin. Geographically, Papua New Guinea is located north of Australia (Figure 1). A large amount of offshore seismic data was gathered in the early 1970's. The Papuan Basin is considered to be a frontier basin due to the majority of test wells lacking hydrocarbon shows. However, large economically viable hydrocarbon plays have been discovered in various onshore and offshore locations. These discoveries are promising indicators of future undiscovered hydrocarbon plays throughout the basin. Geological trends, basinal development, and hydrocarbon migration of the Papuan Basin remain widely debated. Global economic interest in hydrocarbon exploration drives continued research in frontier basins all over the world. Because of this continued interest, academic and private researchers have attempted to develop a detailed basin and geological analysis of the Papuan Basin.



Figure 1: Satellite imagery of Papua New Guinea. *Source:* “Papua New Guinea.” 6°33′22.60″S 146°06′27.37″E. **Google Earth.** December 13, 2015. January 5, 2017.

Advancement in the understanding of the Geology within Papua New Guinea was conducted by the Australasian Petroleum Company in 1961 (Rickwood, 1968; Thompson, 1967). However, continued exploration and development has been hindered by the high risk/reward association of hydrocarbon plays within the basin. Few advancements into the Geology of Papua New Guinea have been made since the initial data collection in the early 1970’s. The lack of physical core data, combined with large geographical gaps in well log data, has generated inconsistent interpretations among scholars. Continued modeling and interpretation of the Papuan Basin is important for two reasons: 1) it provides updated hydrocarbon models using more advanced modeling software, 2) it allows for better understanding for future commercial oil and gas development. With the advancement of computer programs, existing well data can be analyzed to better understand the development of hydrocarbon resources within the Papuan Basin. With a detailed understanding of basinal stratigraphy and structure, correlation between oil/gas producing wells will provide a better analogue for the hydrocarbon production in the

basin. In addition to producing wells, dry wells within the basin may provide information on failed prospects. The purpose of this study is to understand the reasoning surrounding limited hydrocarbon production within the extent of the Papuan Basin (Figure 2). Specifically, this study attempts to answer the question of “Why is the Papuan Basin a frontier basin?” Existing data will be used to better comprehend the Geologic processes surrounding hydrocarbon accumulation and reservoir Formation.

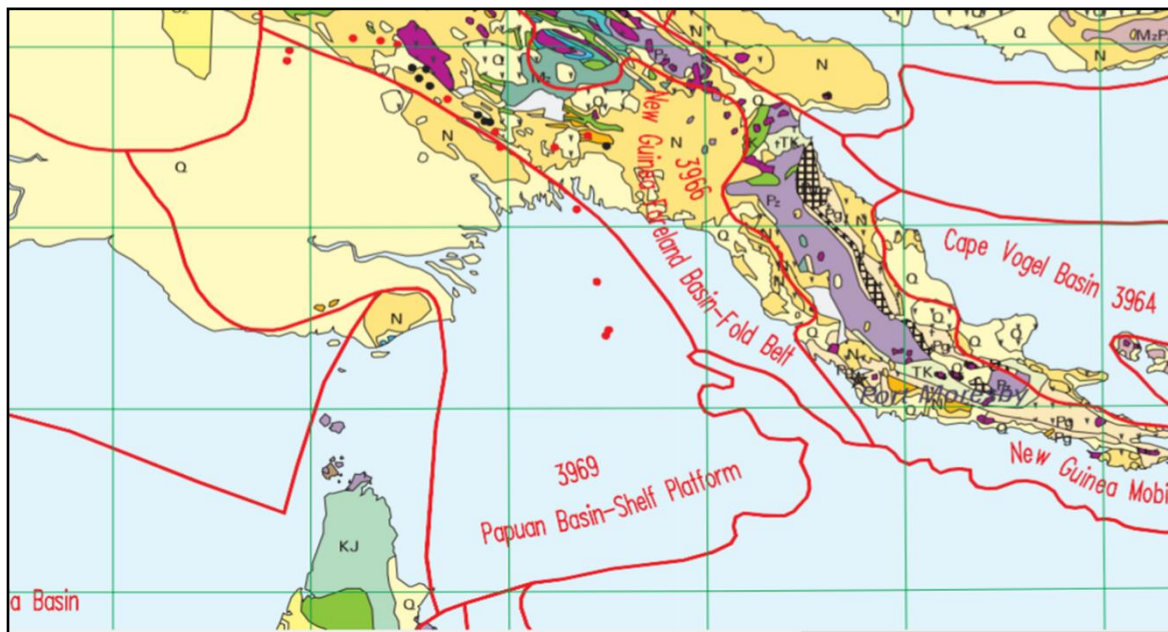


Figure 2: This figure shows the extent of the Papuan Basin and the Shelf Platform (from Steinshouer, et al. 1997). Red dots indicate gas-producing wells. Black dots represent oil-producing wells.

GEOLOGIC BACKGROUND

Exploration History and Hydrocarbon Plays

The island of Papua New Guinea has been a prospect for hydrocarbon deposits since early discoveries of oil seeps within the Papuan Fold belt in 1911 (Boult, 1997). Consequently, current oil and gas discoveries have been constrained to the Papuan Fold belt. Limited success in the Western Papuan Basin has plagued recent exploration. The Papuan Basin has a complex structural history, combined with significant uncertainty surrounding the hydrocarbon generation and migration history (Earnshaw et al. 1993). Discoveries of gas in 1986, represented the first major commercially viable discovery in the Papuan Basin (Boult, 1997). The Pale Sandstone was one of the early sedimentary units identified that showed promising reservoir potential (Ahmed et al. 2012). Several exploration wells were drilled in the early 1950's on the onshore portion of the basin following previous discoveries in 1911. More wells were drilled in the following years until the late 1980's. The majority of wells drilled were at depths of less than 1,500 meters (Boult, 1997). Hydrocarbon shows were observed in several of these wells; however, no wells were economically viable at the time (Boult, 1997). Despite a handful of producing wells (Appendix C), the onshore Papuan Basin remains a frontier basin in the early stages of development. Rickwood (1990) identified a potential relationship between the lack of oil seeps, and areas of low population density (Rickwood 1990; Barndollar, 1993). Thus, a correlation between hydrocarbon production and population density may explain the lack of recent discoveries in other remote locations.

Exploration in the offshore Papuan Basin has been targeting Miocene reef systems. The Gulf of Papua is part of the foreland basin that developed because of the collision between the

Australian and Pacific plates (Palinkas et al. 2006). Seismic exploration of the offshore Gulf of Papua has provided data sets for potential hydrocarbon prospects; however, a lack of well control makes interpretation difficult. Roughly 11,770 kilometers of seismic work has been conducted (Wise, 1976). Miocene reef limestones have been intensely studied for trap potential (Durkee, 1990). Early test wells discovered the presence of gas and condensate in Middle Miocene reefs (Wise, 1976). Most notably, the Pasca reef located in the central Gulf of Papua, has been the most productive Miocene well. Middle to Upper Jurassic source rocks in the Gulf of Papua have shown promising hydrocarbon potential within thicker sedimentary units (Thompson, 1965; Gordon et al. 2000). However, the current extent of the Jurassic units is currently unknown. A detailed review of the early hydrocarbon exploration history is adequately represented by reports from the Australasian Petroleum Company and J. E Thompson (Oppel, 1970). Gordon et al. (2000) identified two major Jurassic plays located in the Papuan foreland (Fig. 3) (Gordon, Huizinga and Sublette, 2000): 1) a Jurassic sourced thrust play, 2) a Jurassic sourced rift play. In addition to the Jurassic plays, a Tertiary gas-condensate play is present within Eocene and Miocene carbonates. Figure 3 shows the approximate location of all the Hydrocarbon play locations.

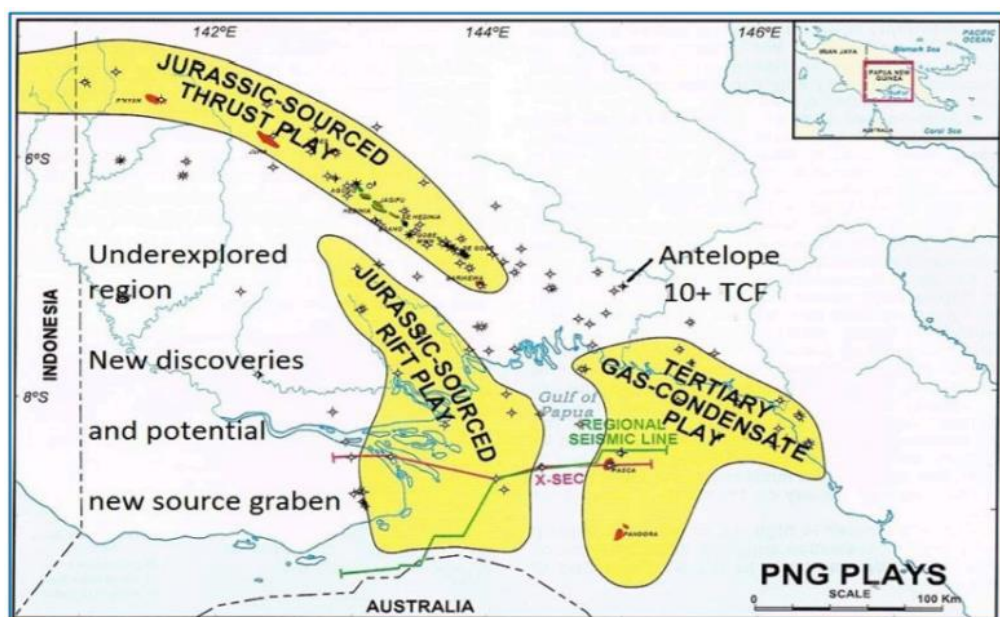


Figure 3: Map of Papua New Guinea showing the location of targeted hydrocarbon plays (from Gordon, Huizinga, and Sublette, 2000.)

The sequence stratigraphy and basinal development of the Papuan Basin have been intensely studied (Harrison 1969; Home 1990; Rickwood 1990; Phelps 1993; Barndollar 1993; Davies et al. 1996). Post-Permian stratigraphy is well known from a long history of field surveys and exploration drilling (Home et al. 1990). The best approach to understanding the sequence stratigraphy of the Papuan Basin is described by Pigram et al. 1990 where all eight megasequences are analyzed independently (Home et al. 1990). Figure 4 represents the depositional megasequence's responsible for development of the Papuan Basin (Home et al. 1990).

Currently, the Papuan Basin is considered to be a foreland basin (Kawagle and Meyers, 1996). During the early Mesozoic, rocks within this area recorded the transition from initial rifting to a passive margin. Ultimately, a foreland basin developed during the Miocene (Kawagle et al. 1996; Winn and Pousai, 2010). Pre-rift rocks within the basin are comprised mostly of

igneous plutons that make pre-Mesozoic reconstruction difficult (Home et al. 1990). The Kubor Granodiorite and the Strickland Granite are the respective names for intrusive igneous rocks in the Western portion of the basin (Home et al. 1990). Pre-rift sedimentary rocks are restricted to the center of the Kubor Anticline (Home et al. 1990). Rifting in the Papuan Basin is largely the result of the breakup of the Australasian portion of Gondwana during the Late Carboniferous (Kawagle et al. 1996). Separation of the Tibetan, Indonesian, and Pacific plate fragments, allowed for the development of early rifting observed within the Papuan Basin (Kawagle et al. 1996). The separated Australasian portion of Gondwana during the Late Carboniferous collided with the Papuan Basin during the Gondwana Syn-Rift at 250-215Ma (Home et al. 1990; Kawagle et al. 1996).

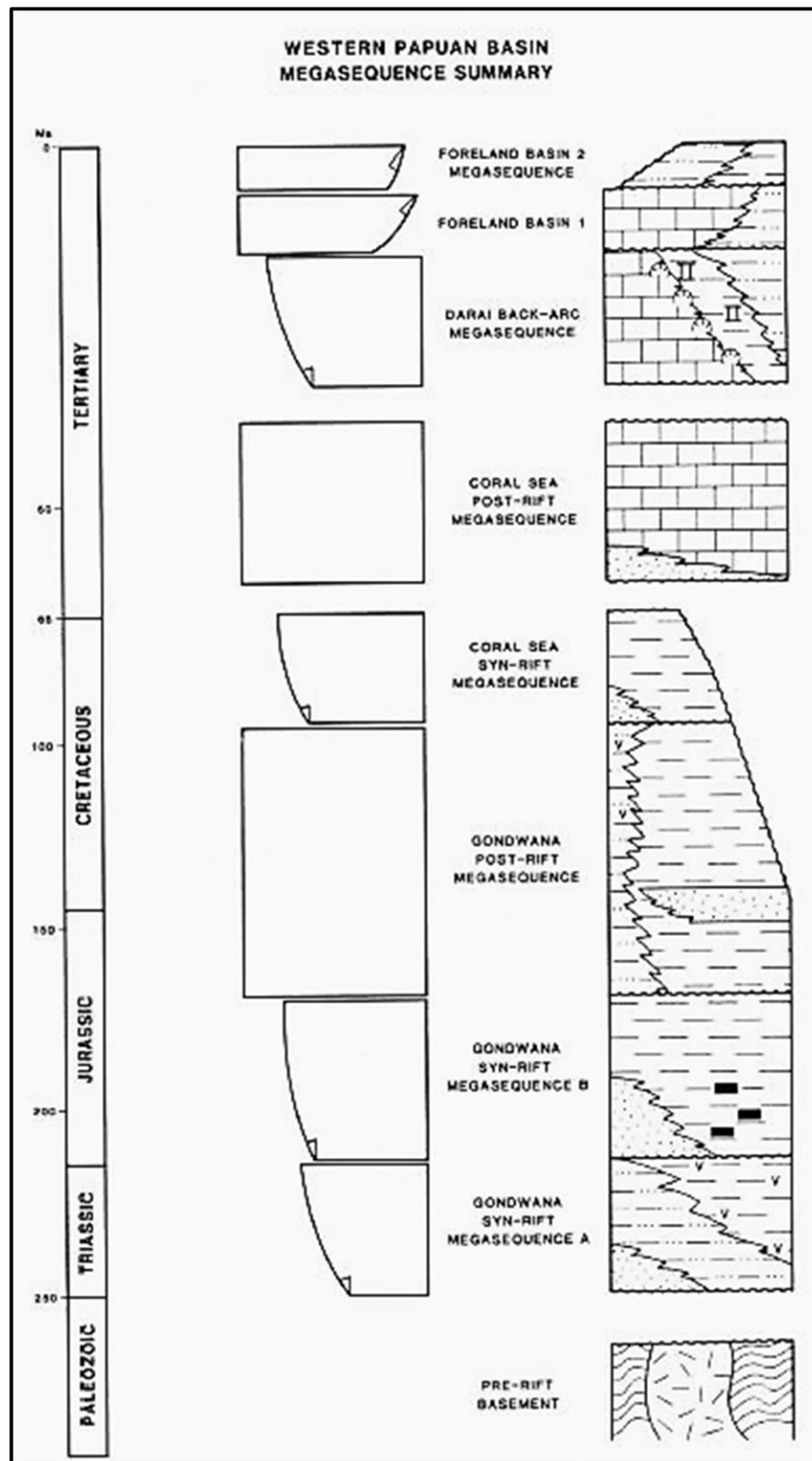


Figure 4: Generalized depositional megasequence summary for the Western Papuan Basin (from Home et al. 1990). Unconformities in this diagram are represented by the lithological gaps in the right column.

The Gondwana syn-rift megasequence propagated in an anti-clockwise direction around the Australasian plate (Home et al. 1990). The young Papuan Basin developed a series of grabens which created the necessary accommodation space for the development of the Papuan foreland (Home et al. 1990; Kawagle et al. 1996). Sediment sourcing took place from the uplifted Papuan Fold Belt to the East and North of the foreland basin. Faulting of the Kubor Anticline in the North has led to the accumulation of approximately 3,500 meters of volcanics and volcanoclastic sediments that sourced from nearby volcanic island arcs (Johnson, 1979; Home et al. 1990). Initial sediment deposition, during Gondwana Syn-Rift megasequence A (Fig. 4), took place as the older syn-rift deposits were overlain by post-rift siliciclastic and volcanoclastic sediments (Kawagle et al. 1996).

The Gondwana syn-rift megasequence A transitions into megasequence B (Fig. 4) during the Early to Mid-Jurassic (215-170 Ma) (Home et al. 1990). Rocks consistent with this depositional event are the Bol Arkose, Magobu Coal, Balimbu Greywacke, and the Barikewa Formation (Home et al. 1990; Kawagle et al. 1996). These sedimentary sequences represent a marine transgression and a transition from non-marine to marginal marine sediments (Home et al. 1990). The Barikewa Formation has been identified as one of the potential source beds in the foreland basin (Bird and Seggie, 1990).

The next major depositional megasequence was the Gondwana Post-Rift Megasequence during the Middle Jurassic (170-95Ma) (Fig. 4) (Home et al. 1990). The Papuan Basin developed as a passive margin basin during the Middle Jurassic as a result of sea floor spreading (Home et al. 1990). This megasequence is dominated primarily by fine clastics in a shallow marine shelf setting (Kawagle et al. 1996). The Koi-Iange, Imburu, and Toro Formations are the main

sedimentary units deposited during the Gondwana Post-Rift megasequence (Kawagle et al. 1996). Deposition of the Toro Formation is interpreted as multiple marine regressive phases, with a coarsening upward sequence (Sari, 1990). Overall, this period of time was dominated by a wide scale transgressive sequence taking place during initial Gondwana rifting (Home et al. 1990).

Following the Gondwana Post-Rift, the Coral Sea Syn-Rift Megasequence took place during the Late Cretaceous (95-65 Ma) (Fig. 4) (Home et al. 1990; Kawagle et al. 1996). Thermally driven regional uplift in the Southeastern portion of the Papuan Basin accelerated the erosion and accumulation of approximately two kilometers of sediments (Home et al. 1990). This erosional event is referred to as the Tertiary-Mesozoic unconformity. The major lithological units deposited during this megasequence were the Ieru and Chim Formations (Kawagle et al. 1996). The Tertiary-Mesozoic unconformity overlies the Ieru Formation, and marks the boundary between the Coral Sea syn-rift, and the Coral Sea post-rift (Kawagle et al. 1996). Figure 4 demonstrates the Tertiary-Mesozoic unconformity as a gap in the lithology column between this time interval.

The Coral Sea post-rift megasequence encompasses all deposited sediments that are Paleocene to Eocene in age. This megasequence was identified by Home et al. (1990), as occurring approximately 65-35 Ma (Fig. 4). Siliciclastics in the lower portion of the sequence consist of the Moogli Mudstone, Urubea Sandstone, and carbonates in the upper portion (Kawagle et al. 1996). Carbonates present in the upper portion of the post-rift megasequence are referred to as the Yala, Chimbu, and Nebilyer Limestones (Home et al. 1990; Kawagle et al. 1996). Conditions during the Coral Sea post-rift were sufficient to generate widespread

carbonate platform development. Climatic conditions during this rifting phase were tropical as the Papuan Basin migrated around the equator (Harris et al. 1996).

The Darai Back Arc megasequence followed the coral sea rifting phase during the Late Oligocene (35-15 Ma) (Home et al. 1990; Kawagle et al. 1996) (Fig. 4). After deposition of the Darai Limestone during a tectonically stable period, reactivation of the Fly, Komewu, and Darai faults took place during back-arc basin development (Kawagle et al. 1996). Carbonate and clastic sediments comprised the bulk of the deposited sediment during this megasequence. The top of the megasequence is marked by a correlative disconformity (Kawagle et al. 1996). Deposition of large carbonate Formations during this megasequence provide good reflective boundaries for seismic identification.

Two Foreland Basin megasequences follow deposition of the Darai Back Arc megasequence (Fig. 4). These megasequences date from 15 Ma to present day (Home et al. 1990). Widespread basin inversion and regional compression developed after the conclusion of back arc extension (Home et al. 1990). The second Foreland Basin megasequence was a result of Late Miocene collisional tectonics (Home et al. 1990). Uplift of the fold belt and island-arc terrains, provided a sediment source for the accumulation of clastic sediments in the Papuan Basin. Thermal subsidence was widespread in the Gulf of Papua (Kawagle et al. 1996). The major formations deposited during this megasequence are the Orudabi and Apinaipi Formations (Kawagle et al. 1996).

Tectonics of the Papuan Basin

Tectonically, the onshore Papuan Basins complexity is apparent in the extreme structural and stratigraphic discrepancies throughout the basin. The Papuan Basin developed by rifting, thinning, and subsidence of the Australian portion of continental crust during the Mesozoic (Davies et al. 1996). Foreland basin development began in the Cenozoic, which led to eventual thrust and fold belt development during the Pliocene (Davies et al. 1996). Home et al. (1990) laid the framework for basinal development in terms of individual megasequence deposition (Fig. 4). Brown et al. (1978) subdivided Papua New Guinea into three major geotectonic provenances: The Papuan Platform, the Central Orogenic Belt, and the Northeastern Island Arc Province (Brown et al. 1978). The Papuan Basin contains the Papuan platform and the offshore Gulf of Papua region. A north-west to south-east trending rift system developed during the Triassic as a response to the break-up of Gondwana (Hirst and Price, 1996). Extensional tectonics led to a series of horst and graben faulting and trough development. These structures provided the necessary accommodation space for siliciclastic deposition. Figure 5 shows the lateral stratigraphic change in siliciclastic deposition. Tertiary compressional tectonics encompasses much of the hydrocarbon traps within the Papuan Basin (Hill et al. 1996).

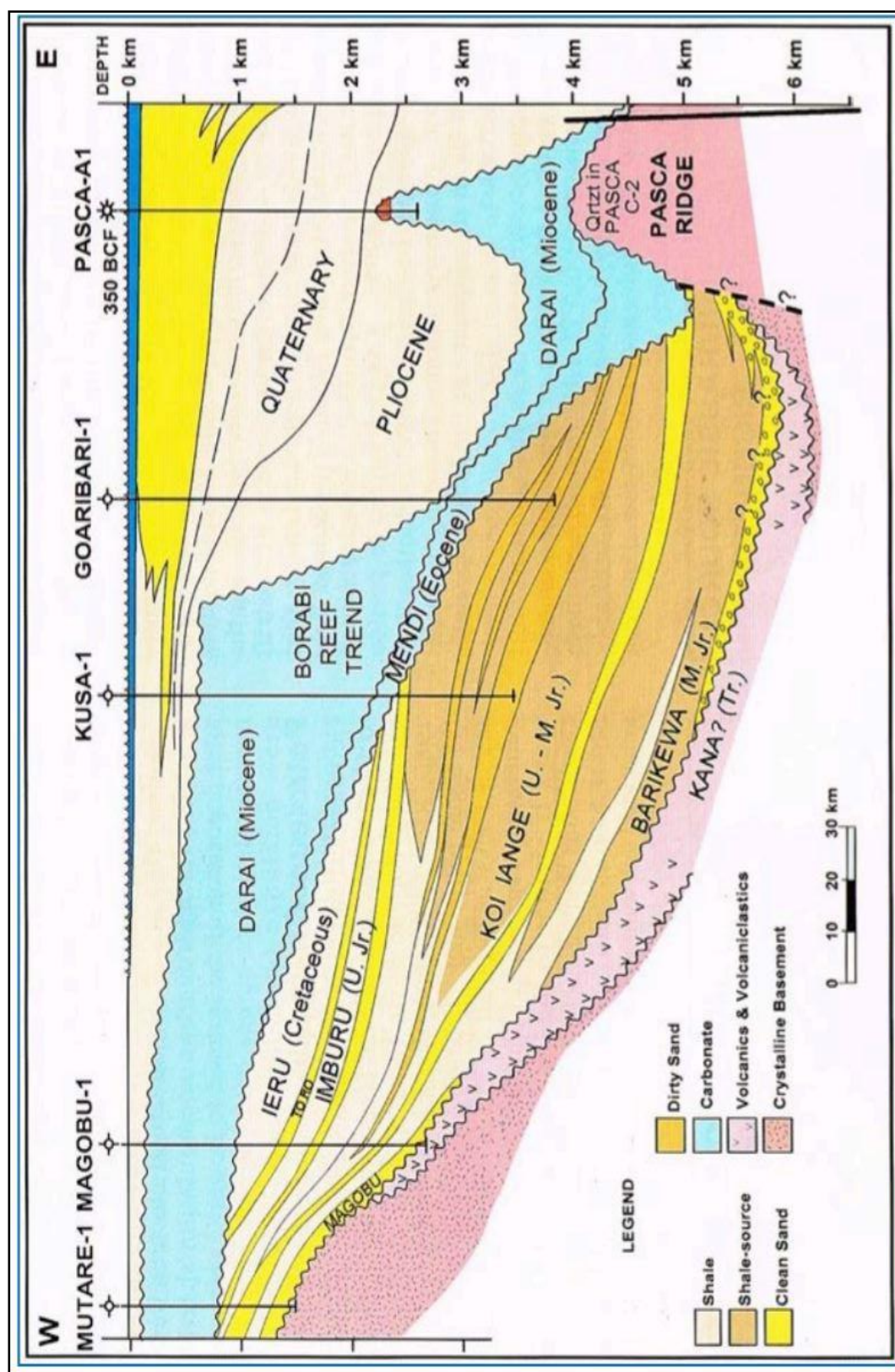


Figure 5: This figure shows a geologic cross section across part of the Papuan Basin. This image demonstrates siliciclastic deposition (from Gordon et al. 2000).

Late Triassic to Middle Cretaceous was an important time frame for hydrocarbon generation and accumulation (Barndollar, 1993). Rift grabens are identified as optimal exploration locations for hydrocarbon deposits. In addition to rift structures in the Papuan Basin, wrench faulting is observed in the reactivated Komewu Fault (Barndollar, 1993). Hydrocarbon accumulation is primarily dependent on the presence of intraformational interbedded mudstone seals within deep Jurassic sandstone units (Barndollar, 1993).

The tectonic framework of the Gulf of Papua is relatively unknown before Tertiary time. Structural complexity, and overlying Eocene strata have made a tectonic framework reconstruction difficult (Wise, 1976). However, recent advancements in seismic imaging allow us to observe pre-Tertiary structural features. The structural opening of the Gulf of Papua took place during the Triassic to Mid-Jurassic as a result of rifting (Gordon et al. 2000). *En echelon* diapiric mudstones, which are approximately Eocene in age, are related to compressional tectonics in the eastern Gulf of Papua (Wise, 1976). The currently mapped tectonic and structural elements within the Papuan Basin are shown in Figure 6.

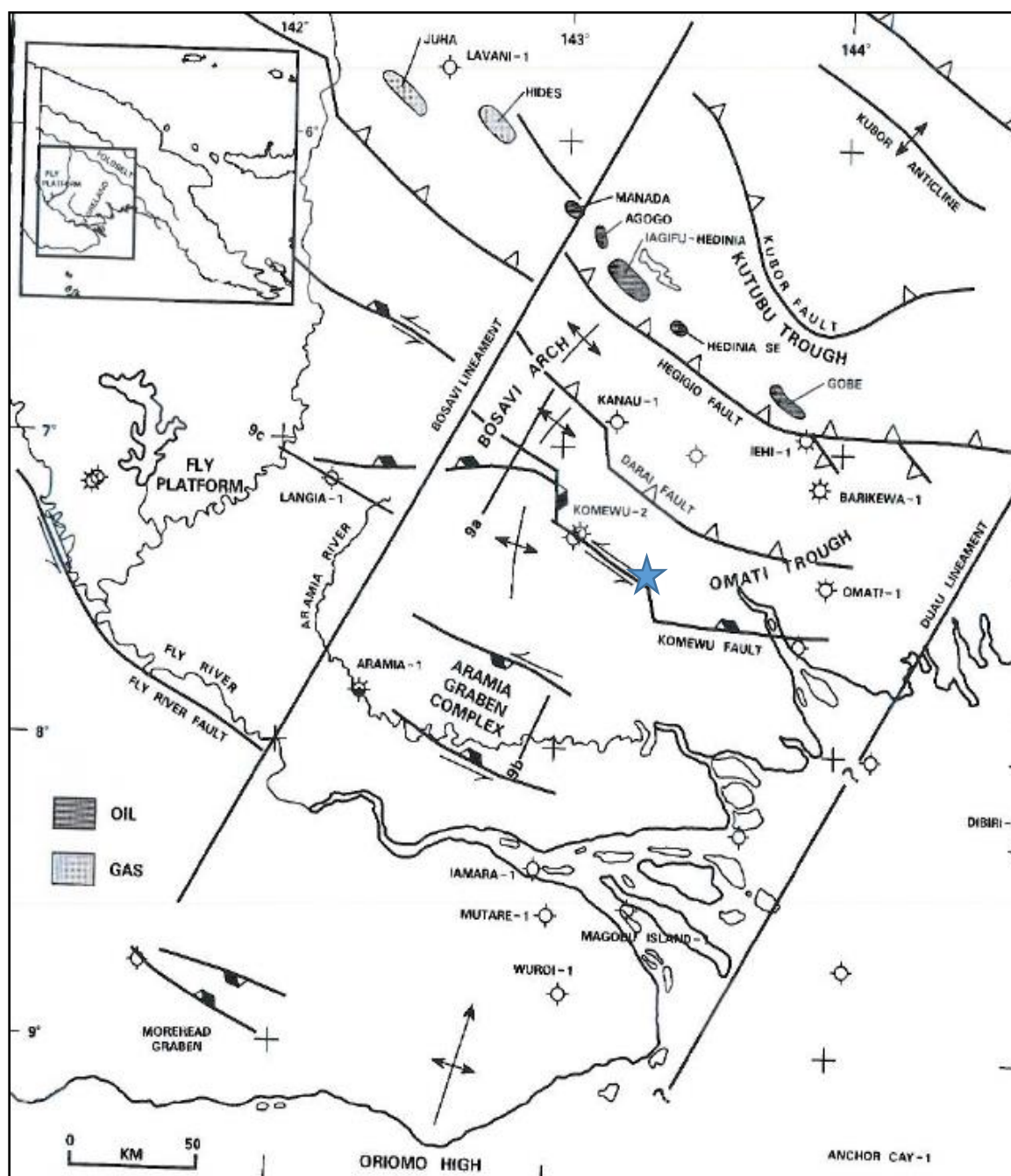


Figure 6: Location map of various tectonic and structural elements within the Papuan Basin from (Barndollar, 1993). The blue star marks the location of wrench faulting observed near the Komewu 2 fault.

Lithology

The Papuan Basin contains a wide variety of lithologies. Lateral changes in lithology are primarily due to development of several mini-basins during extensional tectonics. A generalized stratigraphic column for the Papuan Basin from West to East is represented in Figure 7. Rocks within the basin are Triassic and younger in age. Hydrocarbon discoveries have been made in the Jurassic, Cretaceous, and Miocene units. Lithological characteristics vary widely across the basin because of changes in sediment sourcing. Several correlative unconformities exist in the basin and are shown in a stratigraphic column (Fig. 7). Most notably, a large unconformity is present between the Ieru Formation and overlying marine limestones (Fig. 7). This unconformity is the result of non-deposition (Barndollar, 1993). Jurassic units in the basin have a wide variety of lithologies. One of the lowest Jurassic units is the Magobu Formation. This unit is largely sandstone with interbedded sub-bituminous coal. Above this unit is the Barikewa Formation which varies in lithology from a mudstone to sandstone. Mudstones in the Barikewa Formation are a brown/grey color. Above the Barikewa lies the Koi Iange Formation. This unit is predominantly sandstone with interbedded siltstones. This unit is a light grey in color, and medium grained. The Imburu Formation is primarily a mudstone that grades into a sandy siltstone. The overlying Cretaceous Toro Formation is a coarse-grained sandstone with interbedded mudstone. Parts of the Toro Formation are calcareous. Above the Toro sandstone lies the Ieru Formation. This unit is primarily a very fine grained siltstone that is grey in color. The Ieru is calcareous and pyritic in various intervals. Above the Jurassic and Cretaceous units are the Eocene and Miocene carbonates. Both carbonates are primarily dolomitic limestones. The Miocene Darai unit is a fossiliferous limestone that is slightly less dolomitized than older carbonates.

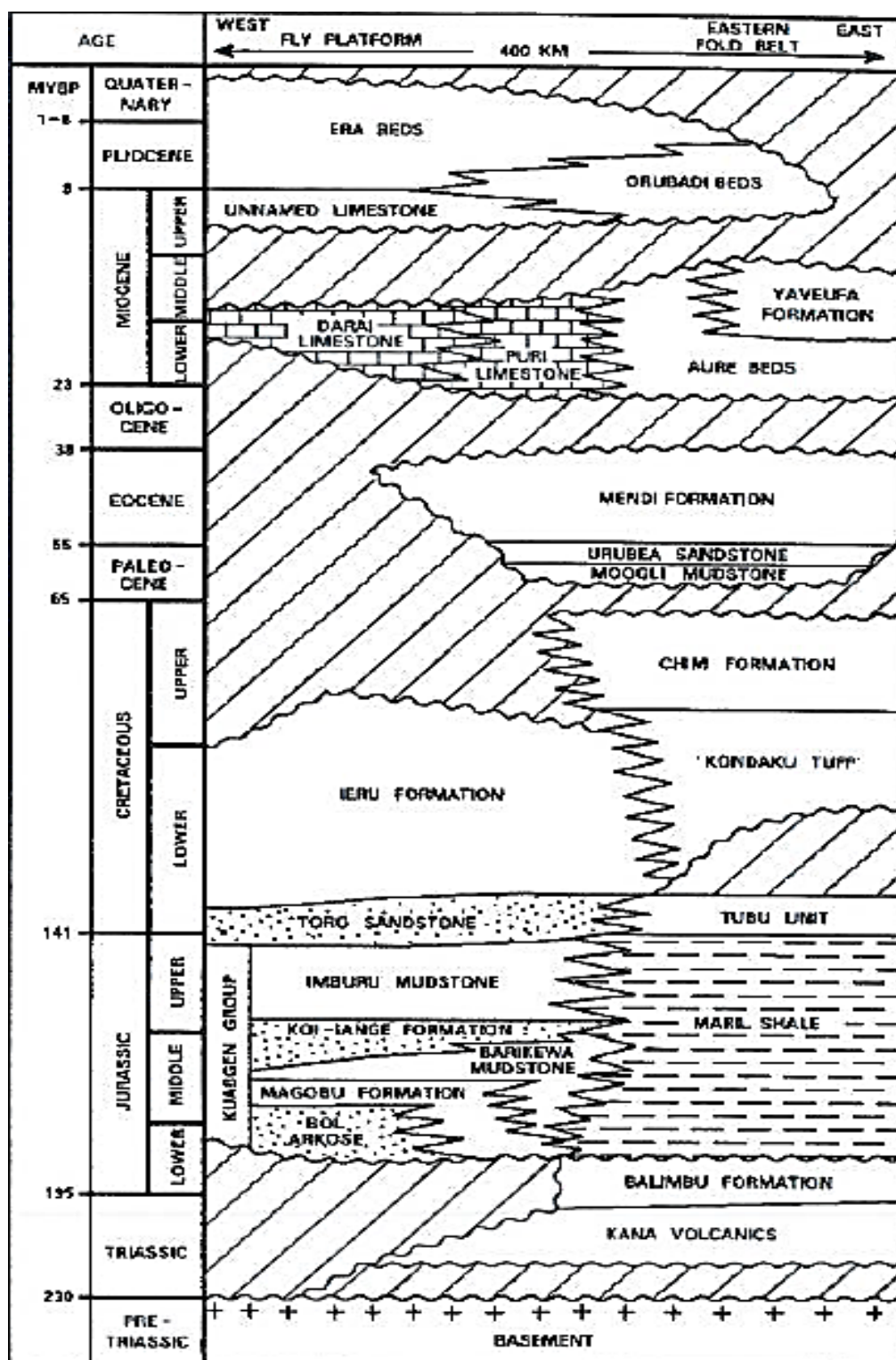


Figure 7: Regional Stratigraphic Column for the Papuan Basin from the Fly Platform to the Eastern Fold Belt (from Barndollar, 1993). Large gaps between units represent unconformities

Stratigraphy of the Papuan Basin

The post-Permian stratigraphy of the Papuan Basin has been thoroughly analyzed from field surveys, and a long exploration history (Home et al. 1990). However, limited amounts of good quality seismic data have resulted in a poor understanding of the structural evolution of the Papuan Basin. In addition, thick sequences of limestone and karst features make seismic imaging and processing difficult (Valenti and Francis, 1996). Individual megasequence boundaries were first identified from Home et al. 1990 (Fig. 4). The first correlation of major unconformities and megasequence boundaries was conducted by BP using well and outcrop samples (Home et al. 1990). Understanding the stratigraphic relationship between the source, reservoir, and seal rocks, is important for future hydrocarbon development.

Mesozoic

Sediment in the Mesozoic was primarily in the form of quartz, sand, silt, and clay that was sourced from the uplifted Australian Shield (Rickwood, 1968). The presence of the Kana Volcanics (Fig. 7) in the Western Highlands suggests a second sediment source from a volcanic arc (Rickwood, 1968).

The Ieru Formation (Fig. 7) is a conformable Cretaceous (late Berriasian to Campanian) silty mudstone. The Ieru overlies the Toro sandstone conformably (Fig. 7), with some evidence suggesting that the boundary is diachronous on a regional basis (Phelps and Denison, 1993). The northeastern Chim Formation (Fig. 7) is the lateral equivalent to the upper Ieru Formation (Phelps and Denison, 1993). Overlying the Ieru Formation is a regional unconformity that is a disconformity on a local scale (Phelps and Denison, 1993). Deposition of the Ieru was consistent with a shelfal environment that was inner to middle neritic (Phelps and Denison, 1993).

However, a gradual deepening during the Albian shifted the deposition of the Ieru to outer neritic to upper bathyal (Phelps and Denison, 1993).

Toro reservoirs, along with other similar Late Jurassic to Early Cretaceous sandstones, were deposited during a eustatic depositional cycle (Madu, 1996). The Toro was deposited during a regressive phase, following an initial transgression and progradational flooding phase (Madu, 1996). Toro Sandstones are interpreted to be barrier bar complexes that deposited during these regressive intervals (Sari, 1990). Lithologically, the Toro Sandstone has 3 distinctive intervals. These intervals consist of: a lower sandstone unit, a middle thick mudstone/siltstone unit, and an upper sandstone unit. The lithology in these units varies; however, the Toro is dominantly a medium bedded, grey, fine to coarse grained quartzose with glauconite (Sari, 1990). Intraformational shales within the Toro can act as hydrocarbon cap rocks for various target zones. Evidence for this is seen in the recent Gobe field discovery where intraformational shales within the Toro have accumulated oil deposits (Surka, 1993). The Toro and Koi Iange Sandstones coincide with regressive cycles (Carman, 1987). Subsidence variations in the Papuan Basin may have caused fluctuations in sea level curves and coastal onlap patterns (Carman, 1987). A better development of Cretaceous sandstones would have taken place to the North and East because of this local subsidence (Carman, 1987).

The major source rock for the Papuan Basin has been identified as a Late Jurassic marine shale that is Late Oxfordian to Late Kimmeridgian in age (Hirst and Price, 1996). This Formation is known as the Imburu Formation (Fig. 7).

Cenozoic

The end of the Mesozoic is marked by a widespread change in the environment in Western Papua New Guinea (Rickwood, 1968). Thick terrigenous and volcanoclastic sediment continued to source from the Western Highlands (Rickwood, 1968). Carman (1987) noted that a global oscillatory highstand during the Early Tertiary resulted in deposition of carbonate units (Carman, 1987; Tcherepanov et al. 2008). Carbonate deposition began during the Maastrichtian and Paleocene, and persisted until mid-Miocene (Davies, 2012). This transgression marks the beginning of the Eocene, in which a thin fossiliferous detrital limestone was deposited in a shallow water shelf environment (Rickwood, 1968). During the Miocene, a second period of marine transgression and deposition resulted in deposition of the Darai Limestone (Fig. 7) (Wise, 1973). During the Late Miocene, reef growth stopped due to the input of clastic sediment deposition from continued erosion of the New Guinea Highlands (Wise, 1973). Overlying Pliocene and Pleistocene sequences are primarily mudstones with sandstone intervals. Conditions during this time were consistent with a deep water tropical environment (Wise, 1973). Diapiric folds occurred within plastic Pliocene mudstones (Wise, 1973).

Potential Source Rocks

Source rocks in the Papuan Basin are Late Jurassic marine mudstones (Burns and Bein, 1980). The Barikewa Mudstone (Fig. 7) has been identified as a promising source rock candidate for wells in the Papuan Basin (Durkee, 1990; Bird and Seggie, 1990). However, this unit is only present as the basin approaches the Papuan Fold Belt. Other Jurassic units that are likely candidates for oil sourcing are the Magobu, Koi-Iange, and Imburu Formations (Fig. 7). The Imburu Formation is a promising source rock due to the widespread occurrence in the Papuan Basin. Jurassic units within the Papuan Fold belt have previously been identified as major source rocks for the region (Morton et al. 1996). Boulton (1993), discovered 64.6 meters of reservoir grade Imburu Formation in an exploration well (Boulton, 1993). An average porosity of 11.6% and an average permeability of 117 md were calculated in the Imburu (Boulton, 1993). Graben's and basement lows provide the most promising locations for maturation of the Imburu.

Potential Reservoir Rocks

Conventional reservoirs are the primary targets for exploration projects in the Papuan Basin. Late Jurassic to Cretaceous sandstone reservoirs have shown to be the most promising for development. During the mid-1980's the Late Cretaceous Pale Sandstone was identified as a promising reservoir (Ahmed et al. 2012). Most recently, the Lower Cretaceous Toro sandstone and its lateral equivalent have shown promising reservoir potential with a porosity range of 20-30% (Gordon et al. 2000; Bennett et al. 2000). Reservoir rocks, like the Toro Sandstone, may be sealed by the overlying Cretaceous Ieru Formation or intraformational shales (Fig. 7).

METHODS

Data Collection

Data for this project area was donated to Ball State University by L. Bogue Hunt. This database is commonly referred as the “Hunt Database”. The database contains well-log data, lithological data, drilling reports, 2D seismic data, structural maps, and geological reports for various exploration sites. A large portion of the Hunt Database is comprised of physical well-log data and numerous seismic lines. Well-logs contain lithological, geochemical, and paleontological data. Additionally, gamma ray, spontaneous potential (SP), and resistivity data are available for each of the wells within the Papuan Basin. Geographical locations for each of the well sites are provided in the form of Latitude and Longitude. Shot-point and navigation data for 2D seismic lines are provided in their corresponding navigation logs.

Data Preparation

In order to construct meaningful geologic maps, the original data from the Hunt Database was processed to become suitable for mapping programs. Well-log data was collected and entered into an Excel sheet. Well names, locations, and total depth were recorded. Values were entered in meters for continuity. Gamma ray, SP, and resistivity logs were extracted from the database, and calibrated manually for depth scales. Formation tops were picked from a combination of lithological data, and changes in the recorded values from gamma ray, SP, and resistivity profiles. These tops are important marker points for stratigraphic correlation. Rock descriptions were provided in well reports where drill cuttings and core data was available. Drilling remarks were important for understanding hydrocarbon shows and production rates present within each well.

Database Construction and Utilization

The mapping program Petra was used to construct a database for the Papuan Basin. Petra is a useful program for the construction and interpretation of geologic maps, cross-section lines, and 3D models. Collected well-log data was entered into Petra in the form of an uncalibrated raster image file. This image file allows for the manual entry of Formation tops and depth values for each well location. Physical information such as the Kelly Bushing Elevation, total well depth, and geographic location were entered into the database to produce a point on the map symbolizing the well. Georeferenced Tiff images were used to construct the outline of Papua New Guinea. A corresponding symbol was assigned to each well to describe the production potentials observed in the drilling remarks. These symbols are available in Table 1.

Table 1: This table consists of well symbols used within the Petra database. Well symbols were assigned based off of well log information provided from the Bogue Hunt Database.

WELL SYMBOLS	
	Gas Well
	Oil & Gas Well
	Dry Hole
	Gas With Oil Show
	Gas Show
	Abandoned Well
	Dry Hole With Gas Show
	Abandoned Water Injector

Once a database for the Papuan Basin was constructed, various mapping tools within Petra were made available. Detailed contoured grid maps were constructed for each Formation top within the basin. A depth to basement map was used to analyze sediment distribution and sedimentary thickness across the basin. Geologic cross-sections were constructed through

various wells to correlate stratigraphic units, and infer structural features. Isopach maps were created to analyze Formation thicknesses for the Ieru and Imburu Formations. Several 3D models were created using Petra's 3Dviz Simulator. Cross sections and 3D models were analyzed using an 18x vertical exaggeration to identify subsurface structures. Seismic data was analyzed for structural features that extend out into the Gulf of Papua.

RESULTS

Well-logs were plotted geographically within the database based on their Latitude and Longitude (Fig. 8). Well symbols in this location map coincide with symbols in Table 1.

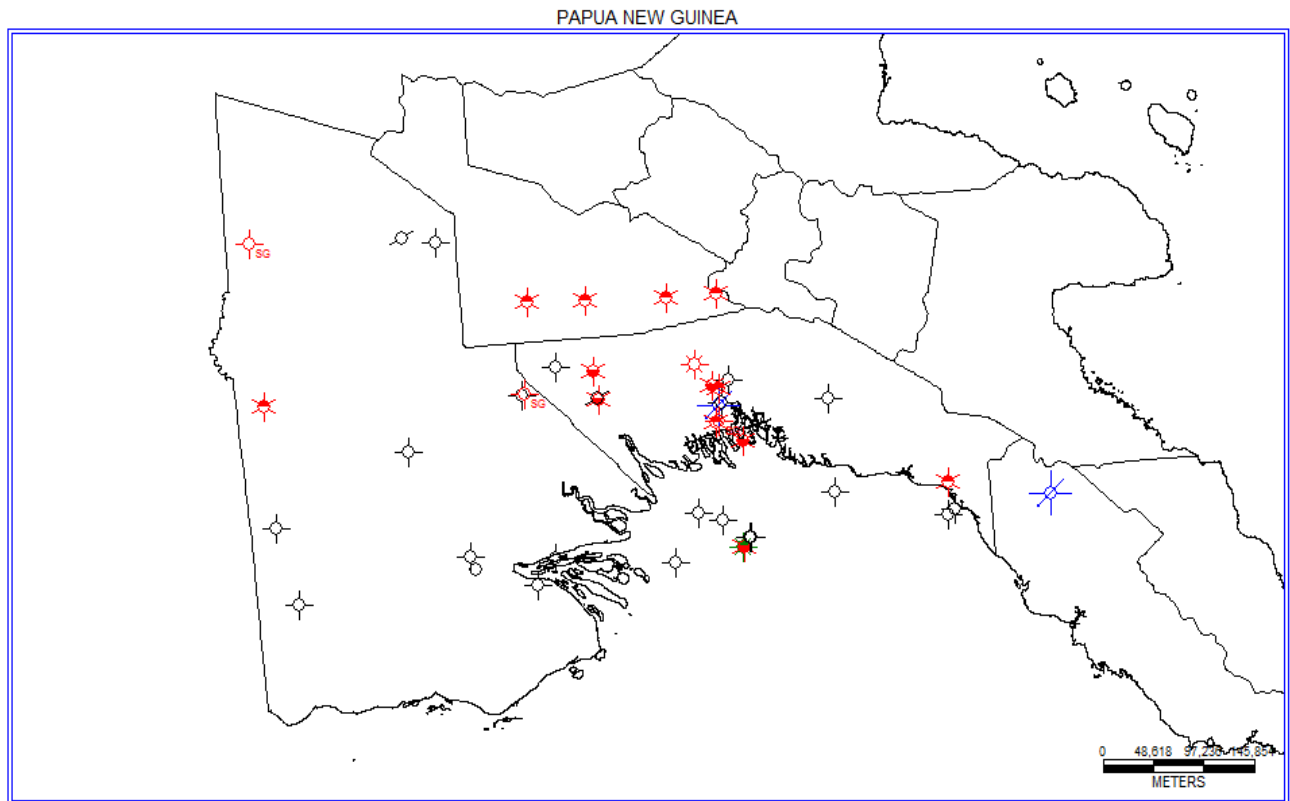


Figure 8: Map of Papua New Guinea. This map shows the distribution and type of wells located across the Papuan Basin. North is located up in this figure.

The locations of several normal and reverse faults throughout the basin are modeled based on subsurface data in Figure 9. Seismic lines were plotted on this image to show the location of seismic collection in the Gulf of Papua. Structural faults were identified and plotted on the map (Fig. 9).

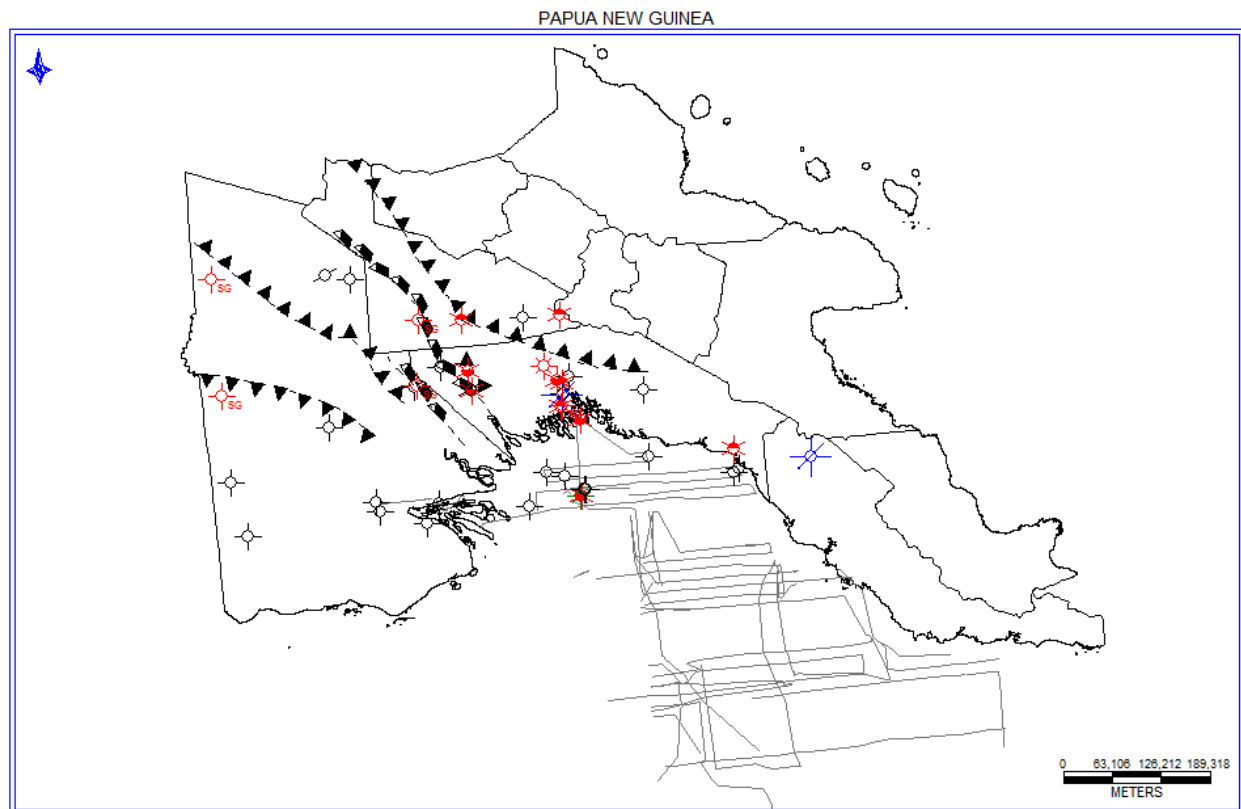


Figure 9: Structural map of Papua New Guinea showing some of the major Jurassic fault systems. Light gray lines indicate seismic lines present in the Gulf of Papua. Normal and reverse fault locations are indicated on the map. This map was constructed using Petra. North is located towards the top of this map. (Fault locations modified after Home et al. 1990; Mollan and Blackburn, 1990; Wilson et al. 2013).

Fault locations were plotted from formation top contours and interpreted subsurface cross sections. Figure 10 shows the location of interpreted fault structures throughout the Papuan Basin. The faults are correlated to the 3D model of the Ieru Formation, and show the interpretation of fault structures from the limited well data (Fig. 10).

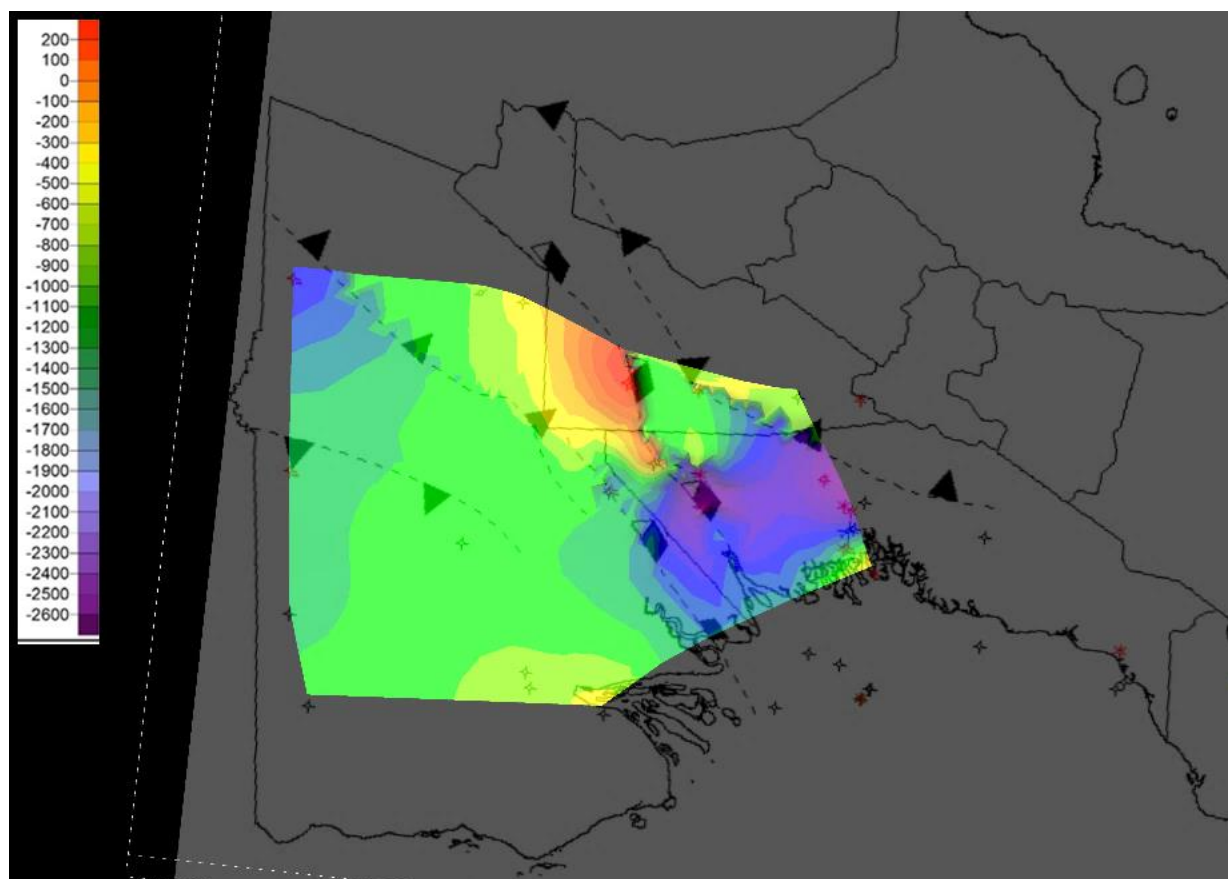


Figure 10: Model showing the interpreted thrust fault and normal fault locations in reference to the Jurassic-Cretaceous units in the Papuan Basin. The faults are overlain on the constructed 3D model of the subsurface depth of the Ieru Formation. The corresponding color bar scale is shown in meters.

A contoured structure map of the basement rock was constructed in Figure 11. Depth to basement rock was calculated and modeled using Petra's gridding software. A significant portion of wells in the basin did not reach basement rock. As a result, the data is modeled based off the extent of the data in the wells. Figure 11 shows a basement high located on the Western portion of the Papuan Basin at an approximated depth of 1,900 meters. A deepening trend towards the East as the basin approaches the Papuan Fold Belt is also observed. A trend in productive wells can be correlated with basement lows (Fig. 11).

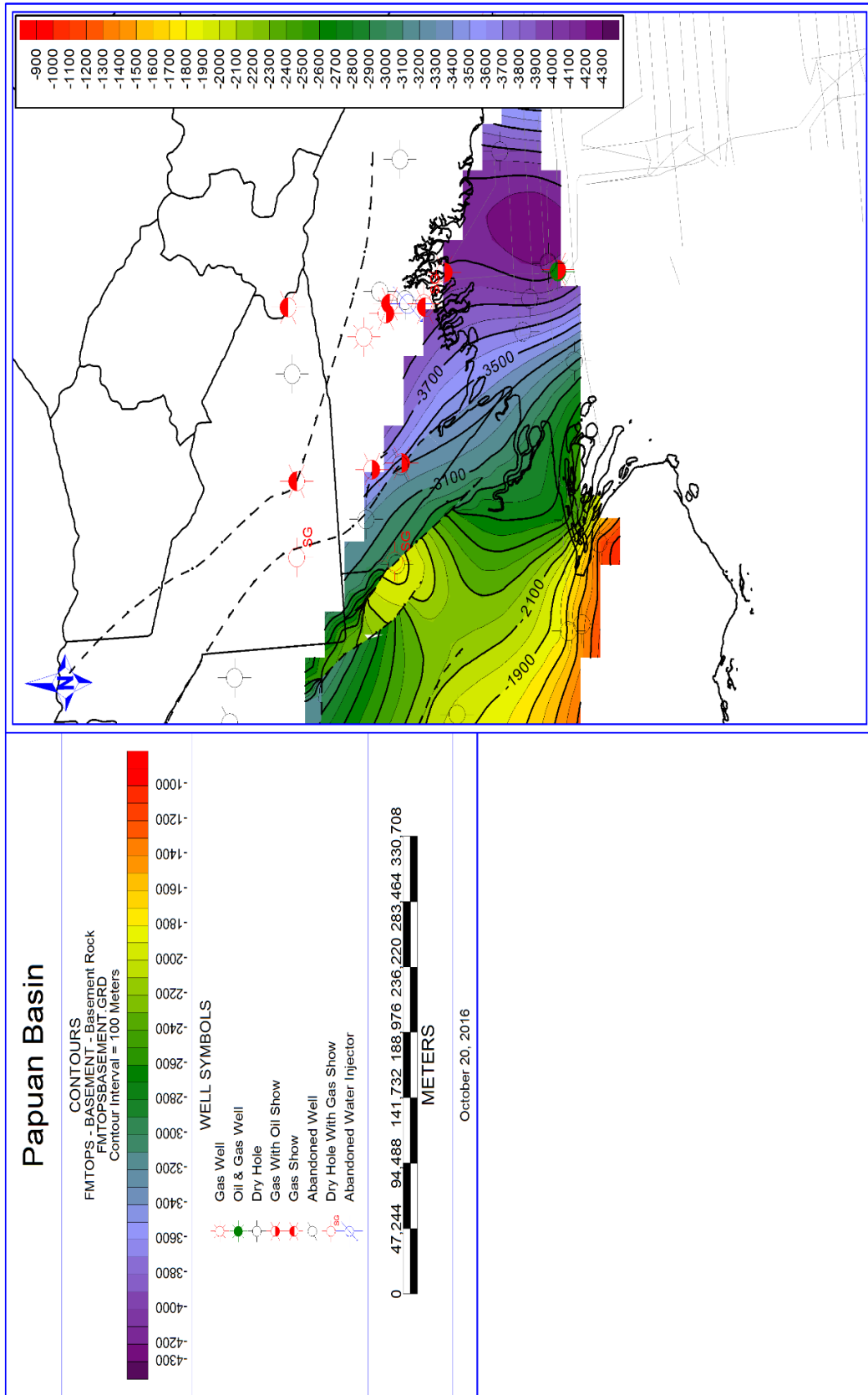


Figure 11: Constructed basement contour map demonstrating depth to basement rock within the Papuan Basin. Dashed lines represent major faults (reverse and normal). This map was constructed using Petra.

A 3D model of the constructed basement grid map is represented in Figure 12. 3D modeling of the basement top was conducted at a scale of 20x vertical exaggeration to show changing structural features across the Papuan Basin. The location of North in Figure 12 is represented by the blue shaded box.

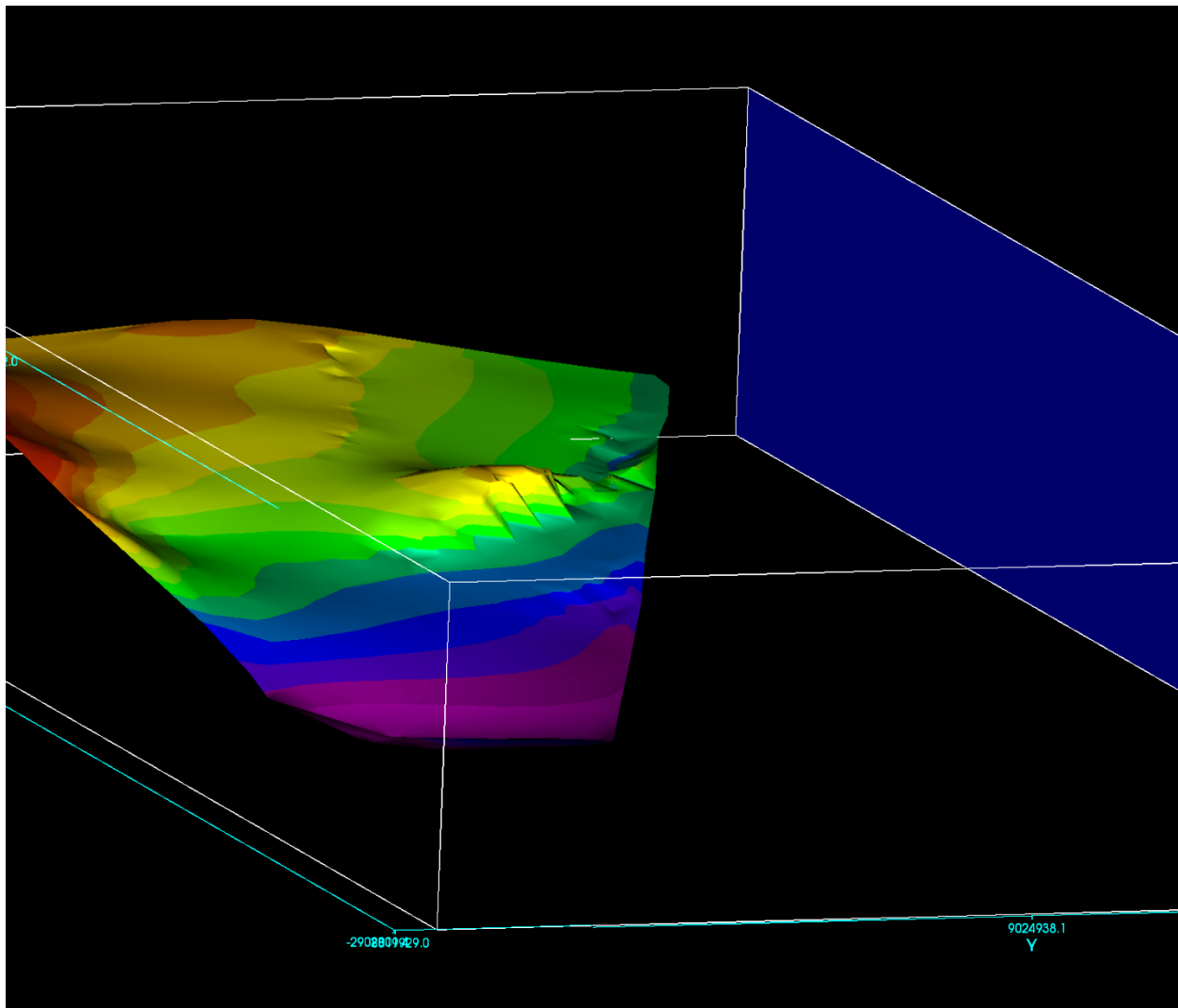
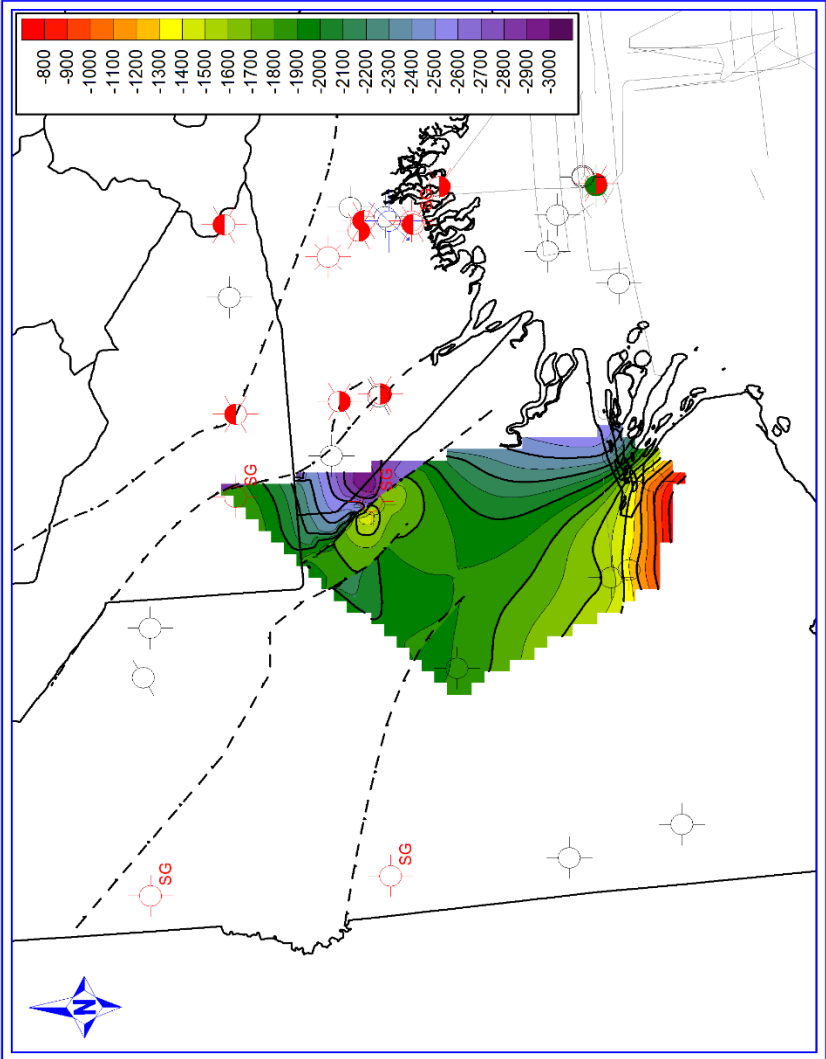


Figure 12: A 3D model of the Basement rock in the Papuan Basin. The blue box represents North. This model was constructed using Petra. VE: 20x. The color scale corresponds to the structural contour map.

Jurassic and Cretaceous Sourced Interval

Figure 13 represents the structural contour map of the lower Jurassic Magobu Formation (Fig. 7). Deposition of the Magobu is restricted to the Southwest portion of the onshore Papuan Basin. The average depth of the Magobu follows a similar trend to the basement depth (Fig. 11). The Magobu Formation has a low source potential and poor reservoir quality as indicated on drilling logs. The Magobu Formation (Fig. 13) was contoured using a 100 meter interval, and assigned a specific color range.



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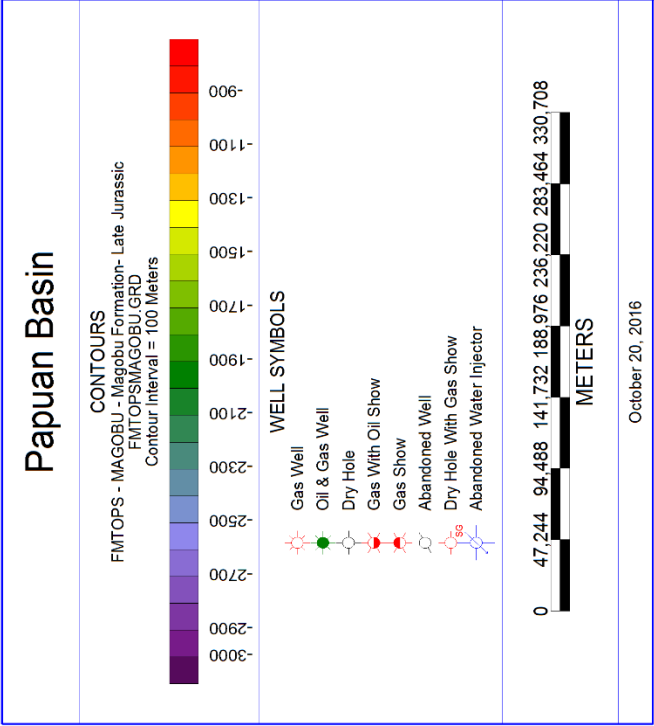


Figure 13: Structural contour map of the Magobu Formation. This formation is Late Jurassic in age, and is one of the earliest deposited units in the Southwestern Papuan Basin. This map was constructed in Petra.

Figure 14 shows a constructed 3D model of the Magobu Formation using Petra. North is represented by the blue shaded box towards the top of Figure 14. Structural features such as basement lows/highs are represented by depth changes.

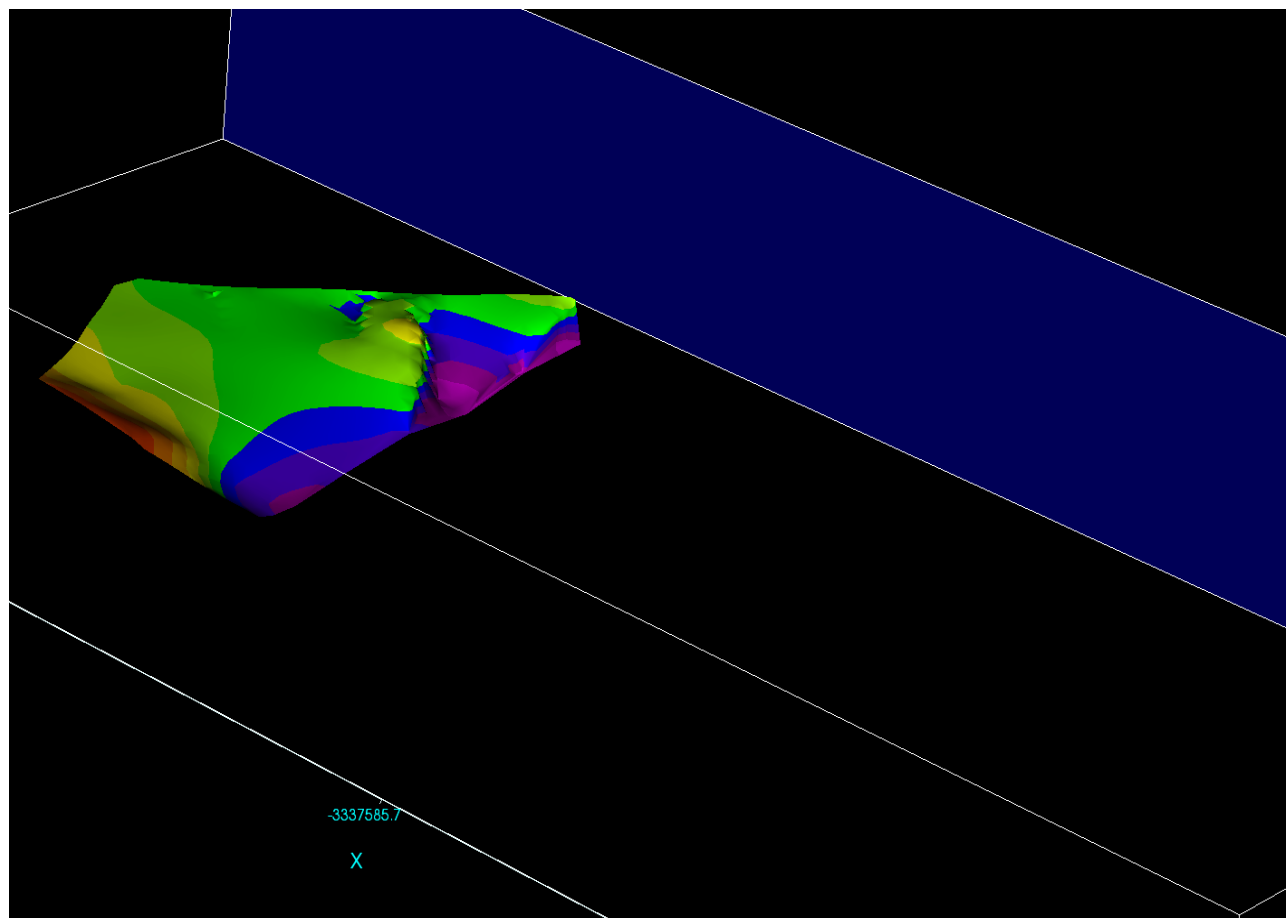


Figure 14: 3D structural model of the Magobu Formation. The blue shaded box represents North. VE: 20x. The color scale corresponds to the structural contour map.

Located above the Magobu Formation is the Middle Jurassic Barikewa mudstone (Fig. 7). The Barikewa Formation is a silty mudstone with interbedded sandstones near the top. Drilling logs indicate this unit has poor reservoir quality and is marginally mature. Figure 15 shows the structural contour map of the Barikewa contoured with a 100 meter interval.

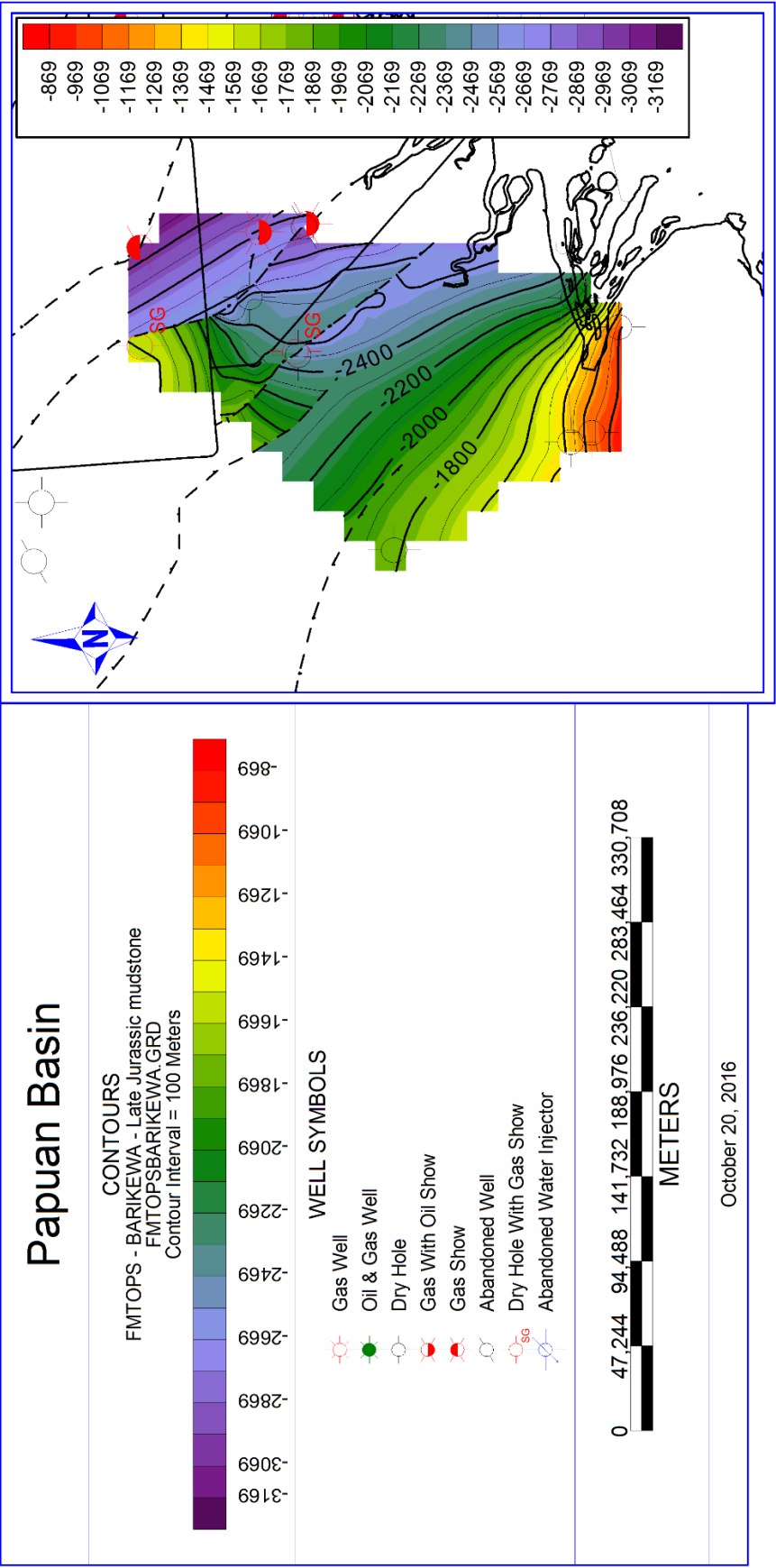


Figure 15: Structural contour map of the Barikewa Formation. Data is extrapolated from well log formation tops.

A 3D model of this stratigraphic unit was constructed in Figure 16 using Petra. Lateral changes in the Barikewa Formation are shown by the varying depths of the unit (Fig. 16).

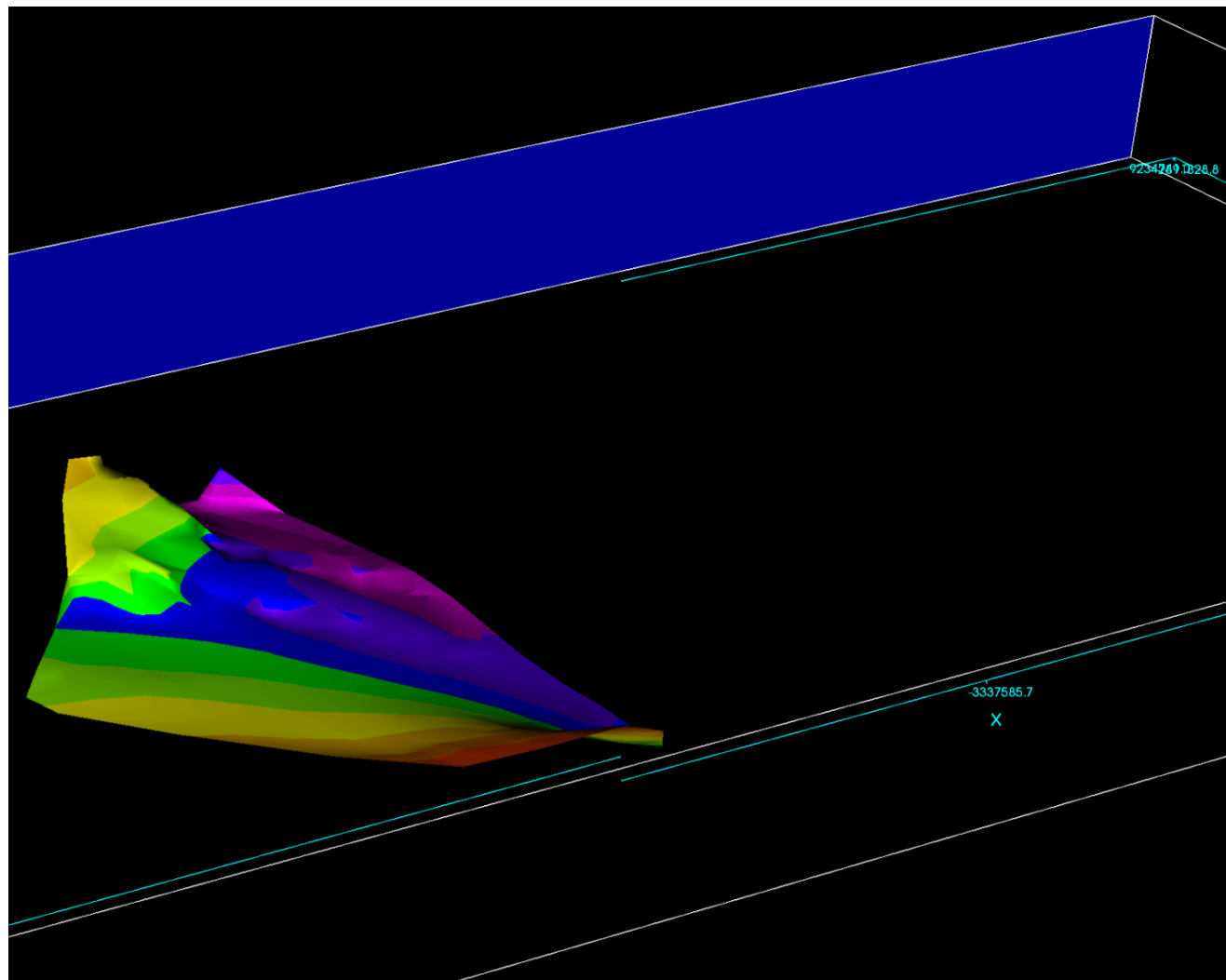


Figure 16: 3D structural model of the Middle Jurassic Barikewa Formation. North is to the top of the page. VE: 20x. The color scale corresponds to the structural contour map.

The Koi-Iange Formation (Fig. 7) is a Late Oxfordian Jurassic sandstone. This unit ranges from coarse to fine grained, and contains cross-bedding with interbedded mudstones. Drill logs indicate that the sandstone has good reservoir potential. A structural contour map of the Koi-Iange is represented in Figure 17.

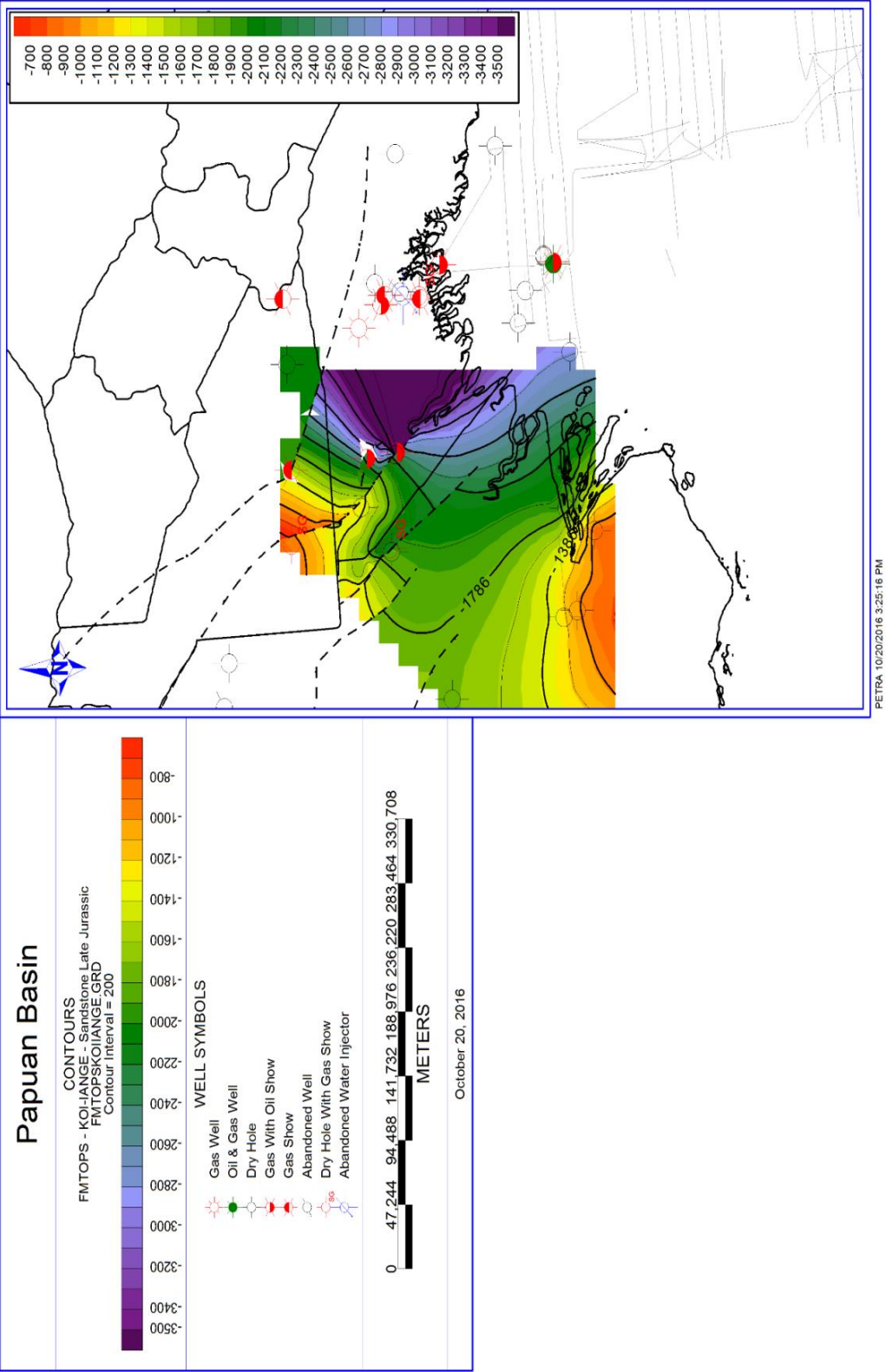


Figure 17: Structural contour map of the Koi-lange Formation.

The constructed 3D model of the Koi-Iange Formation computed from well-log Formation tops is shown in Figure 18. North is represented by the blue shaded region (Fig. 18).

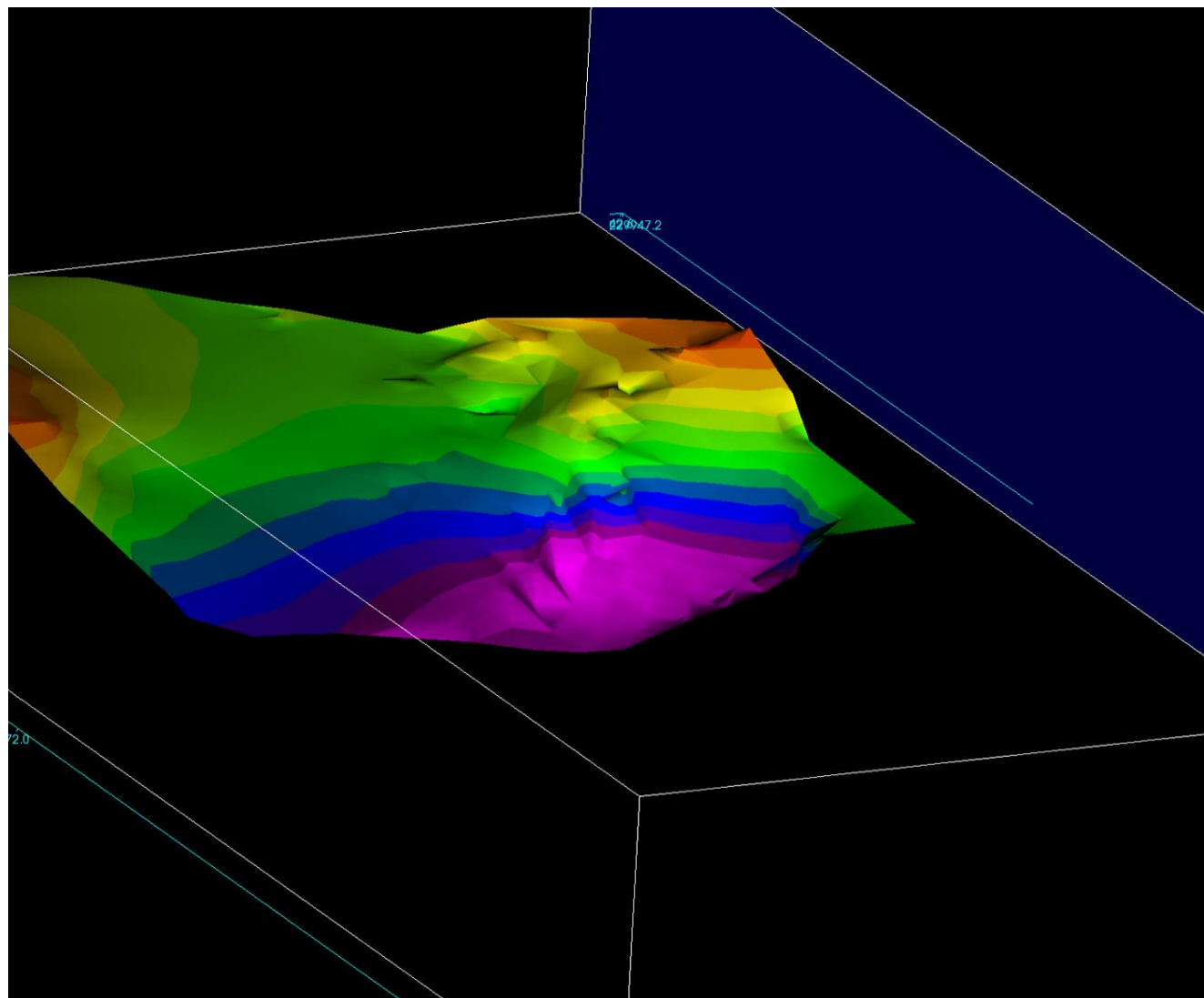


Figure 18: 3D structural model of the Koi-Iange Formation. The blue shaded box represents North. VE: 20x. The color scale corresponds to the structural contour map.

The Jurassic Imburu Formation (Fig. 7) is identified as the major hydrocarbon source bed within the Papuan Basin. The Imburu is an organic rich gray/black mudstone. An isopach map showing the variation in Formation thickness (Figure 19) was constructed. The isopach map (Fig. 19) was constructed for this Formation because the Imburu is recognized as a major source bed in the Papuan Basin.

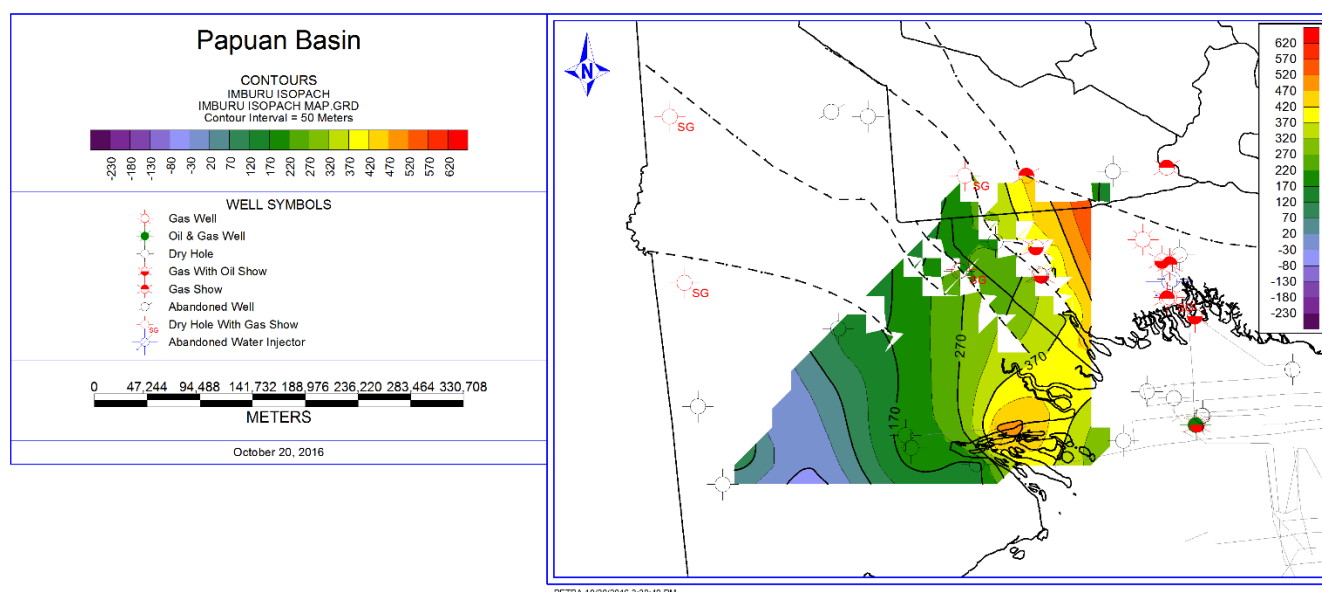


Figure 19: Contoured isopach map of the Imburu Formation. This formation is believed to be the major source bed for The Papuan Basin.

Contour gridding and 3D modeling of the Imburu (Figure 20 and Figure 21), demonstrates the extent of the Imburu Formation within the Papuan Basin. Contour maps are contoured with a 100 meter interval.

Figure 20: Structural contour map of the Jurassic Imburu Formation.

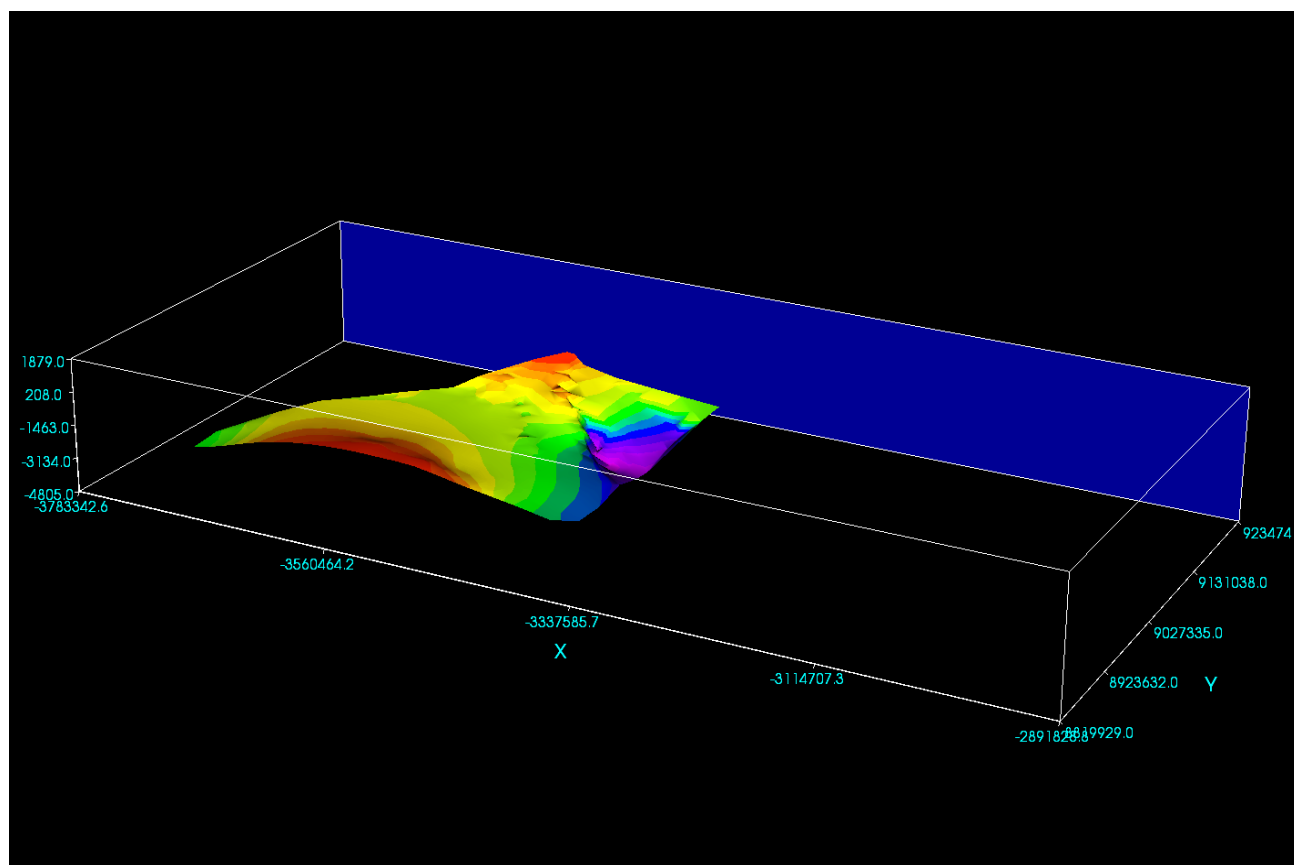


Figure 21: 3D structural model of the Imburu Formation. The blue shaded box represents north. VE: 20x. The color scale corresponds to the structural contour map.

A contoured isopach map of this unit (Figure 22) shows the lateral variation in the thickness of the Toro Sandstone. The Southwestern portion of the basin marks the extent of the Toro. The depth and thickness of the Toro is unknown in parts of the Papuan Basin with no well data (Fig. 22).

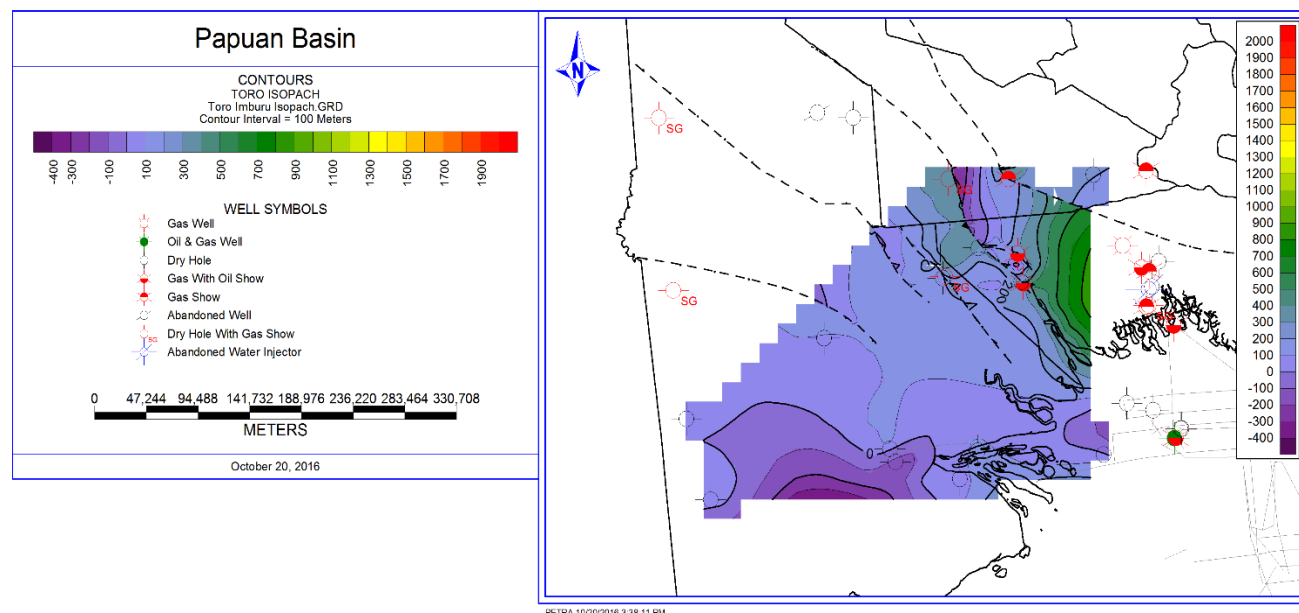


Figure 22: Contoured isopach map of the Jurassic Toro Sandstone. Variations in thicknesses of this unit may correlate to hydrocarbon production and potential.

Well data and structural contouring show a thickness increase and depth increase on the eastern edge of the contour map (Figure 23). Drill logs show that minor production from the Toro has been located on the upthrown block of reverse faults in anticlinal structures.

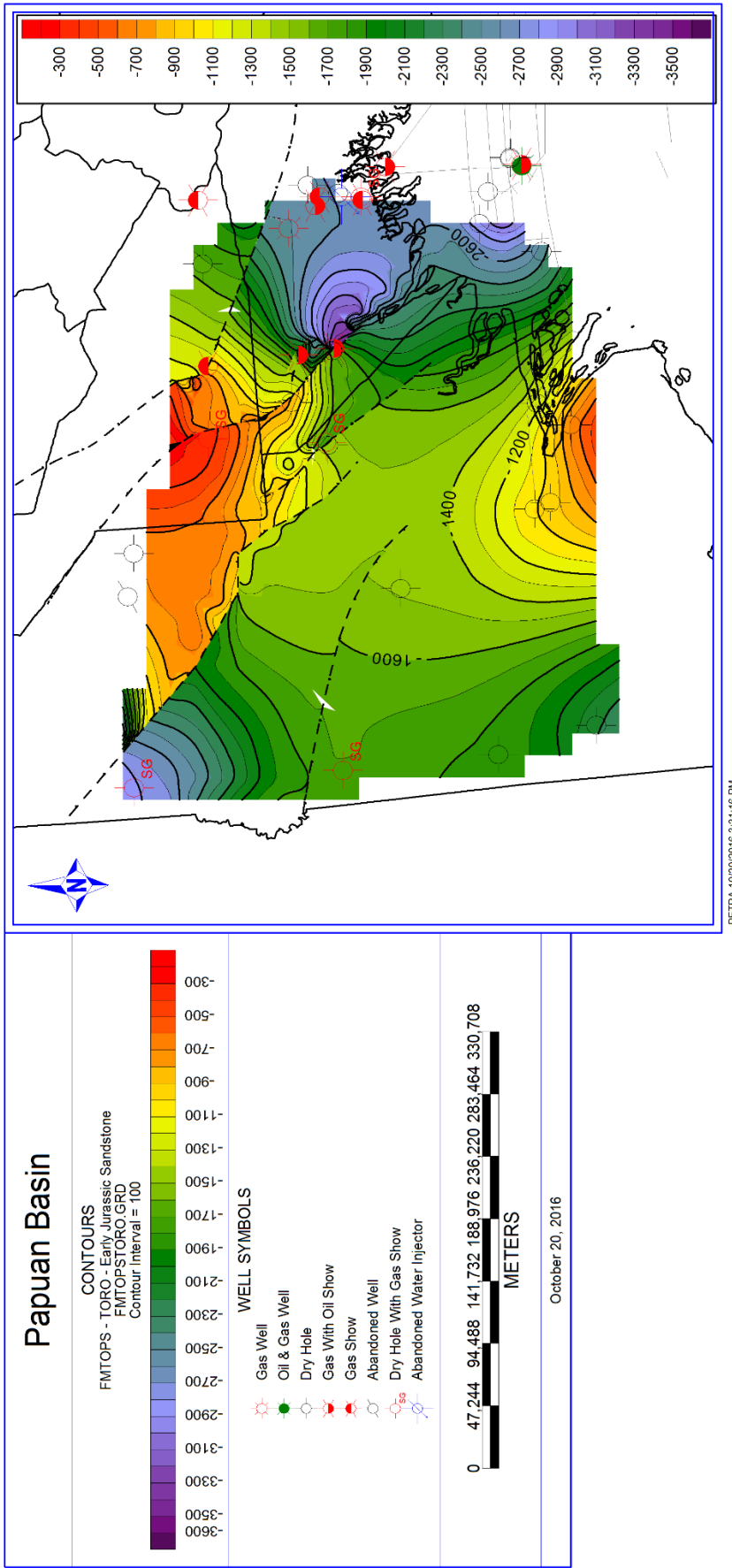


Figure 23: Structural contour map of the Jurassic Toro Sandstone.

Figure 24 outlines the extent of the Toro Sandstone across The Papuan Basin in 3D. The blue shaded region represents North. Structural changes in the formation from faulting are observable in a 3D model (Fig. 24).

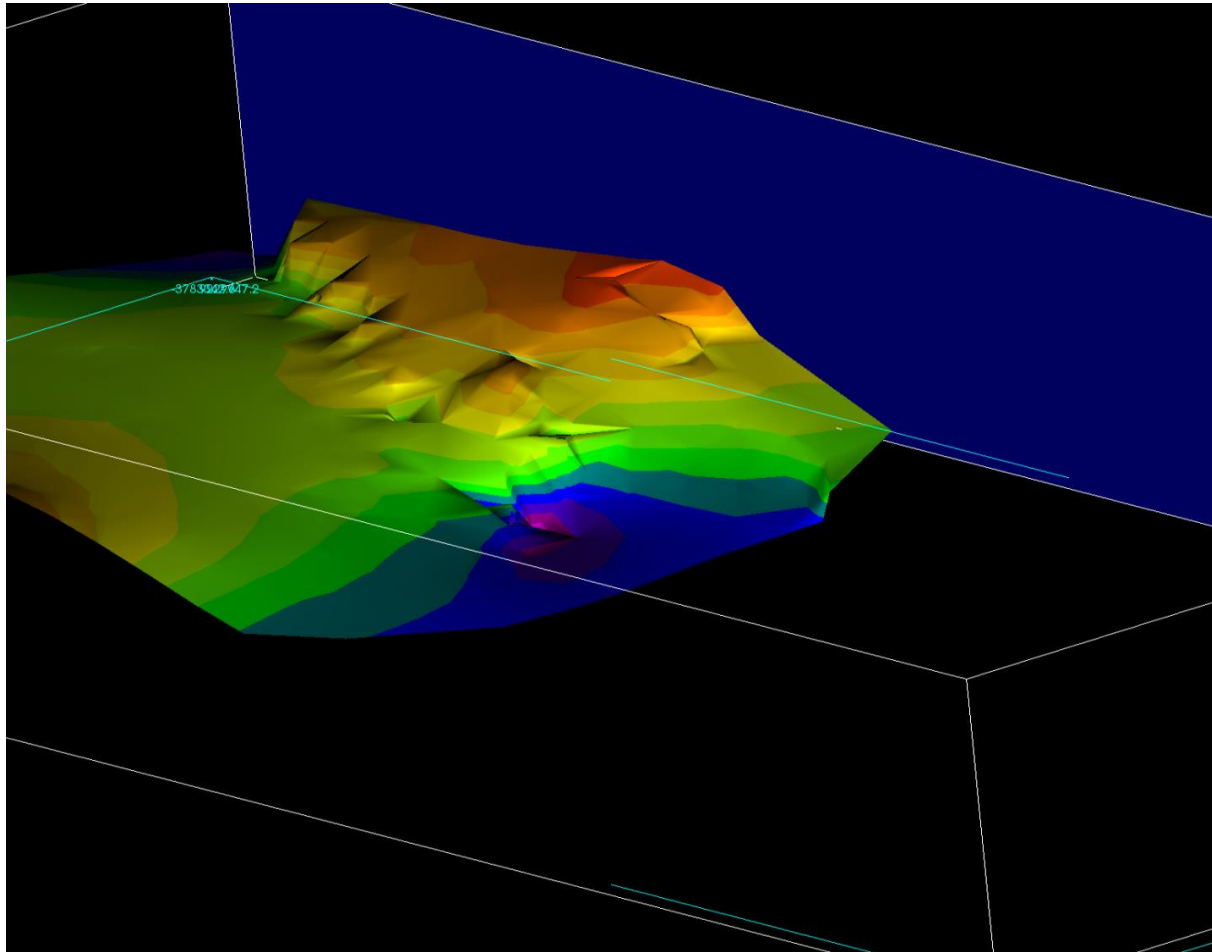


Figure 24: 3D contour map of the Jurassic Toro Sandstone. Reverse faulting, and Horst and Graben structures can be identified. VE 20x. The color scale corresponds to the structural contour map.

The last major unit is the Ieru Mudstone (Fig. 7). The Ieru is identified as Lower Cretaceous in age. This unit is a silty mudstone that overlies the Toro Sandstone (Fig. 7). This unit is widespread across the basin, and varies in stratigraphic thickness. A structural contour map is represented in Figure 25.

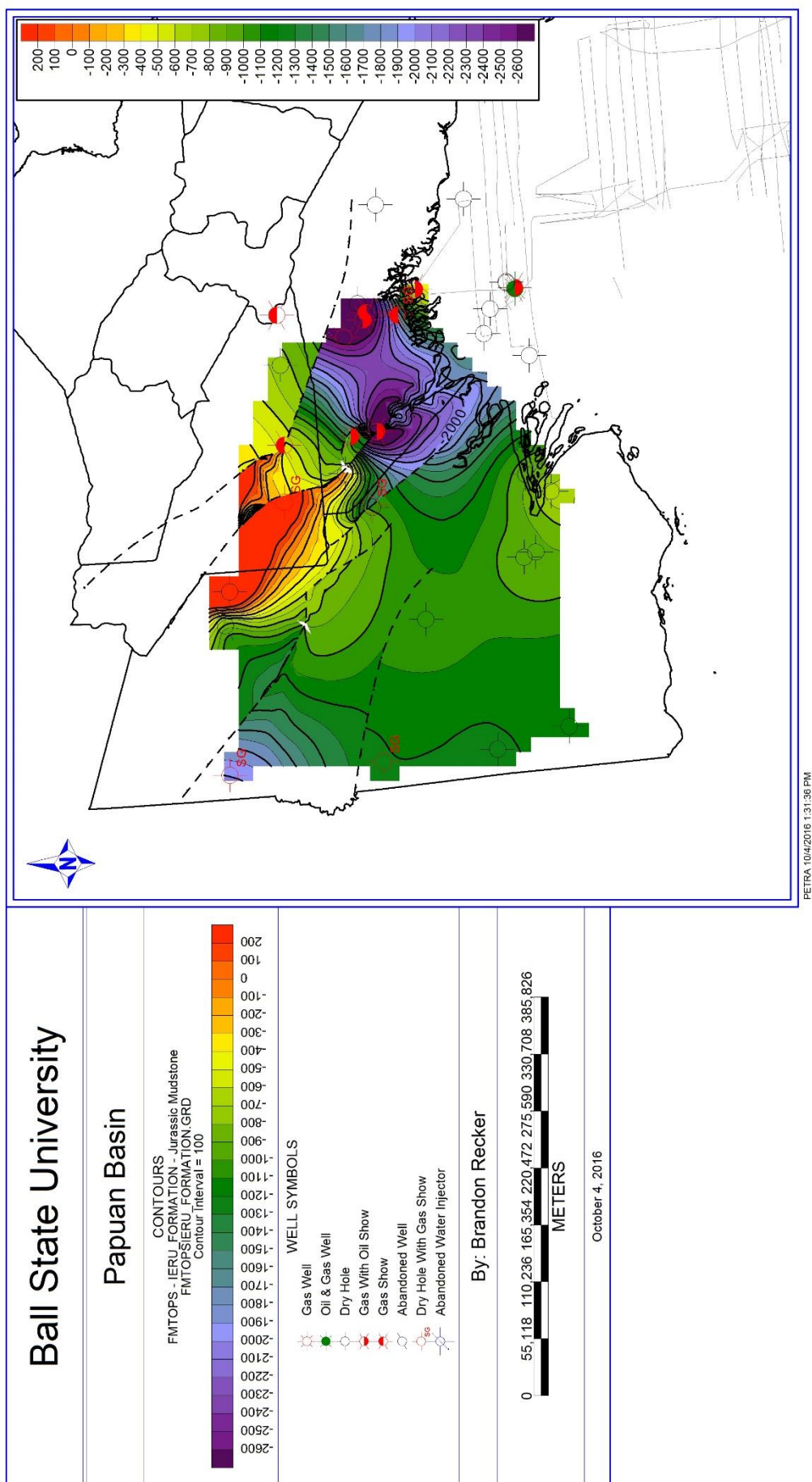


Figure 25: Structural contour map of the Cretaceous Ieru Formation.

Figure 26 shows the constructed 3D model of the Ieru Formation.

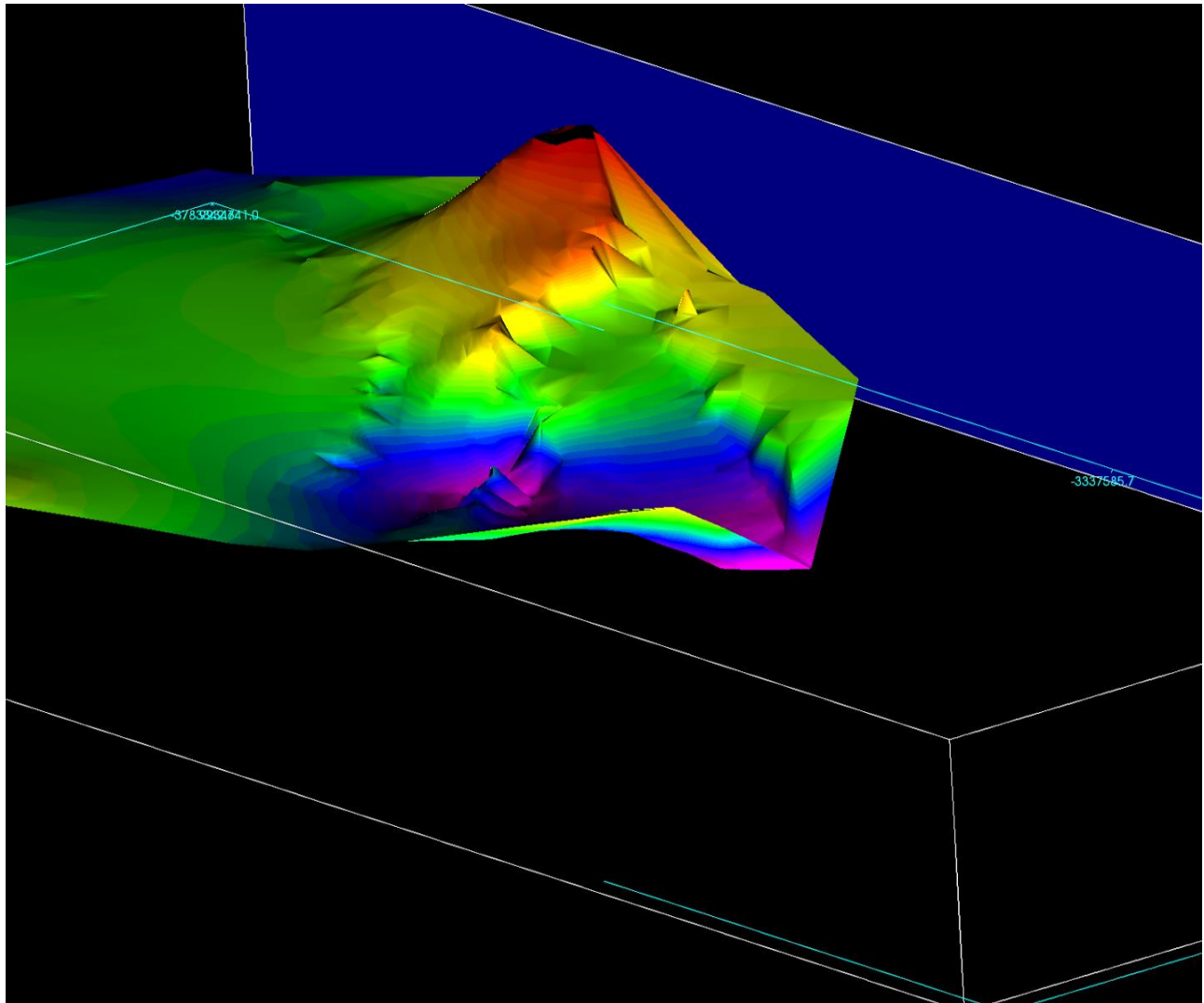


Figure 26: 3D model of the Cretaceous Ieru Formation. Horst and Graben structures are present towards the southern extent of the unit. Reverse faulting is observed in the uplifted portions of the unit. VE 20x. The color scale corresponds to the structural contour map.

Miocene Carbonate Sourcing

The Darai back arc megasequence (Fig. 4) shows the timeframe for the deposition of the Darai Limestone. A structural contour map of the Darai is represented in Figure 27, with the corresponding 3D model in Figure 28. Careful examination of these 3D models allows us to better visualize subsurface data.

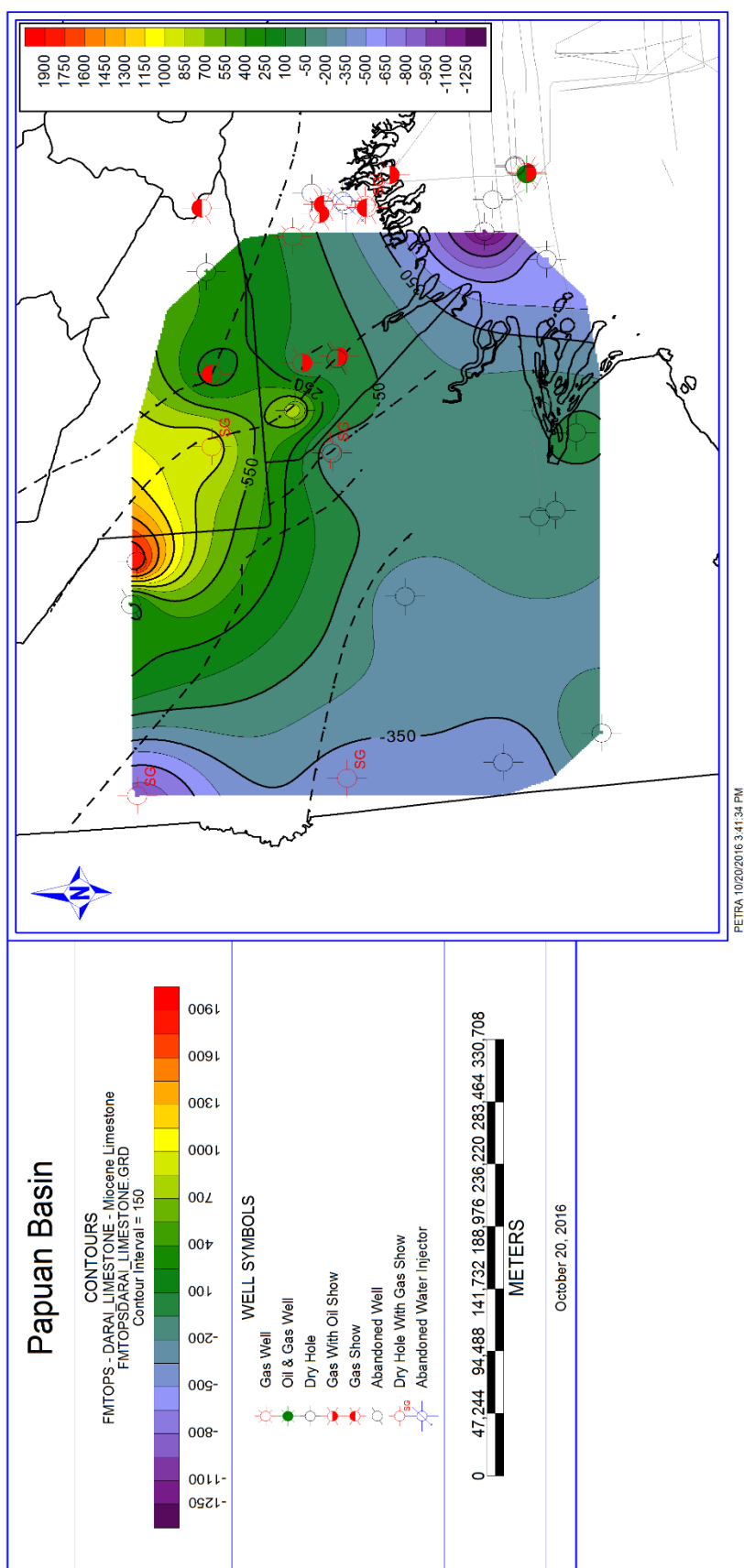


Figure 27: Contoured map of the Miocene Darai Limestone.

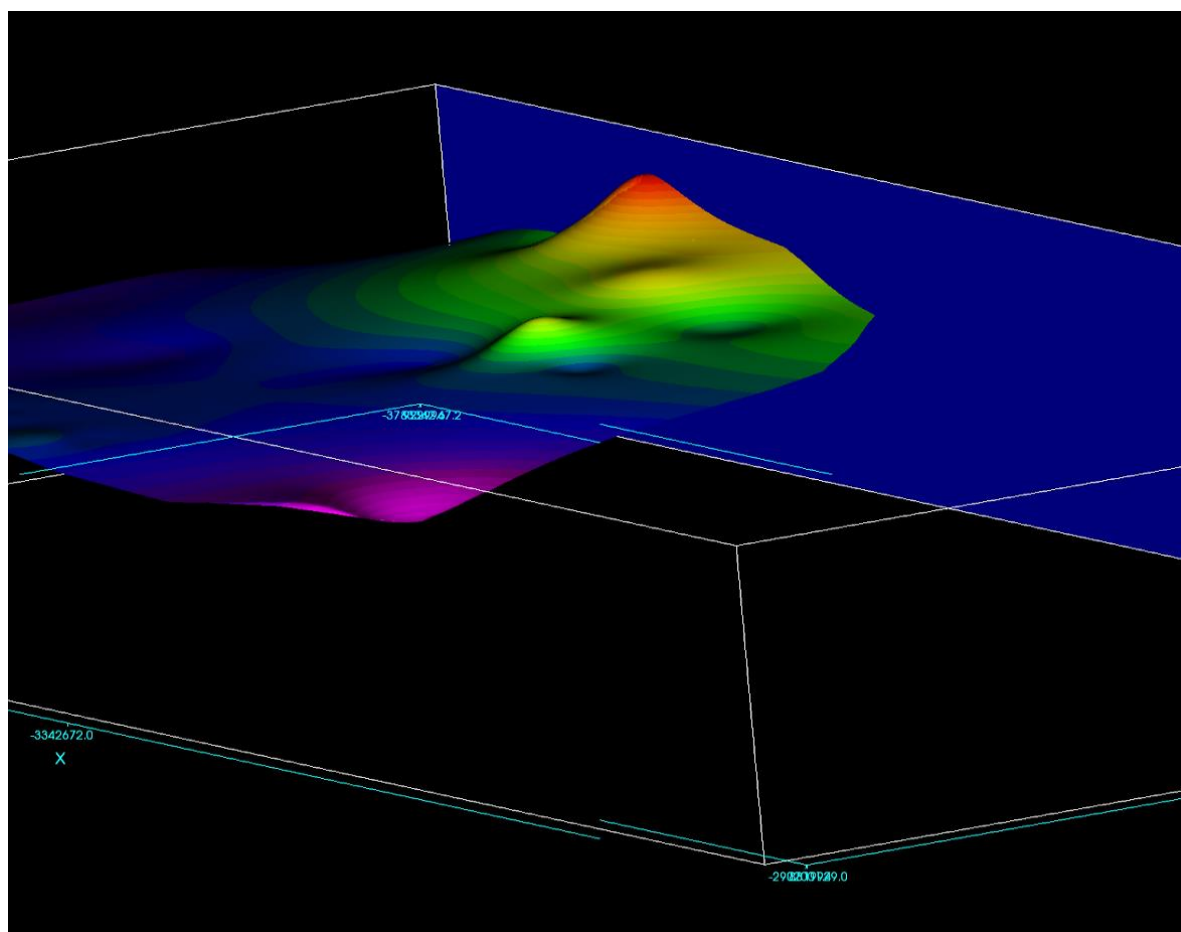


Figure 28: 3D model of the Miocene Darai Limestone modeled using Petra. VE: 20x. The color scale corresponds to the structural contour map.

Structural Cross Sections

Horst and graben structures can be seen clearly in cross sections across the Papuan Basin. Producing Jurassic units are located on the flanks of grabens, where faulting has displaced source units. A cross section line from the Iehi, Barikewa, and Omati 1 wells shows a graben structure (Figure 29) with roughly 1,900 meters of downward displacement. The Barikewa well is present on the flank of the graben, and contains significant oil/condensate and gas production. Drilling logs from the Hunt Database record production amounts for each well within the Papuan Basin. Commercially viable gas was present in this well with flow rates of 2.5 million cubic meters per day. Omati 1 is present in one of the deepest parts of the basin in a graben. Toro Sandstone reservoirs are present in this well at depths of 3,433 meters. Initial gas shows in this well are present at 3,532 meters with a gas brine located at a depth of 3,678 meters. Extractable oil was also noted between 3,900 and 4,200 meters in the Imburu and Koi-Iange Mudstones. The Iehi well, located on the horst, is producing gas at a rate of 32.6 million cubic feet per day (MMCFD). Drill logs show that Iehi is structurally affected by a reverse fault at a depth of 3,900 meters.

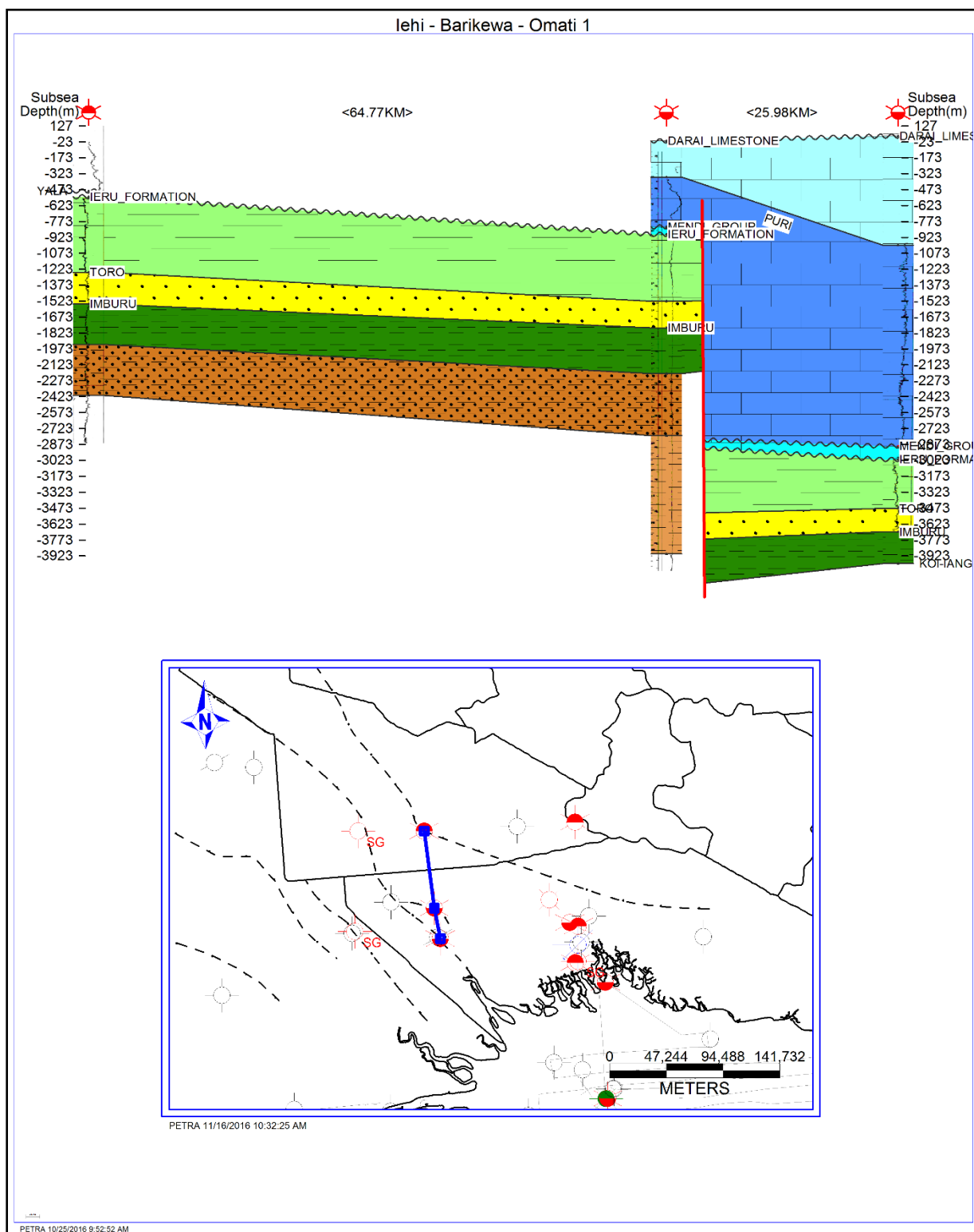


Figure 29: Structural subsurface cross section between the wells Iehi – Barikewa – Omati 1. The red line indicates the location and extent of the horst and graben faulting. The geographical surface location of this cross section line is located in the map. VE 18x.

A subsurface structural cross section between Kanau – Iehi – and Orie was constructed in Petra (Fig. 30). Extensional tectonics are observed in the cross section East of the Kanau well. A thrust fault is identified in the Iehi well by the presence of repeated Jurassic units. This thrust fault was reactivated from compressional flexing of the Papuan Basin. Inclination of the Iehi fault is unknown, and is represented by a vertical fault line in cross sectional view. The repeated Formation tops in the Iehi well are the Toro and Imburu at a depth of 2,715 meters. Precise age dating of these repeated units is currently unknown. Dry gas was produced in the Iehi well between depths of 1,439 and 1,473 meters at a rate of 132.6 MMCFD. The Orie well was drilled to a depth of 2,411 meters, and had no hydrocarbon shows in the Jurassic units. Kanau has some gas shows; however, this well sits on a structural basement high. The Toro and Imburu Formations are present at depths shallower than 2,000 meters, with the exception of the repeated Jurassic section in the Iehi well. The Iehi well terminates before intersecting the Imburu Formation.

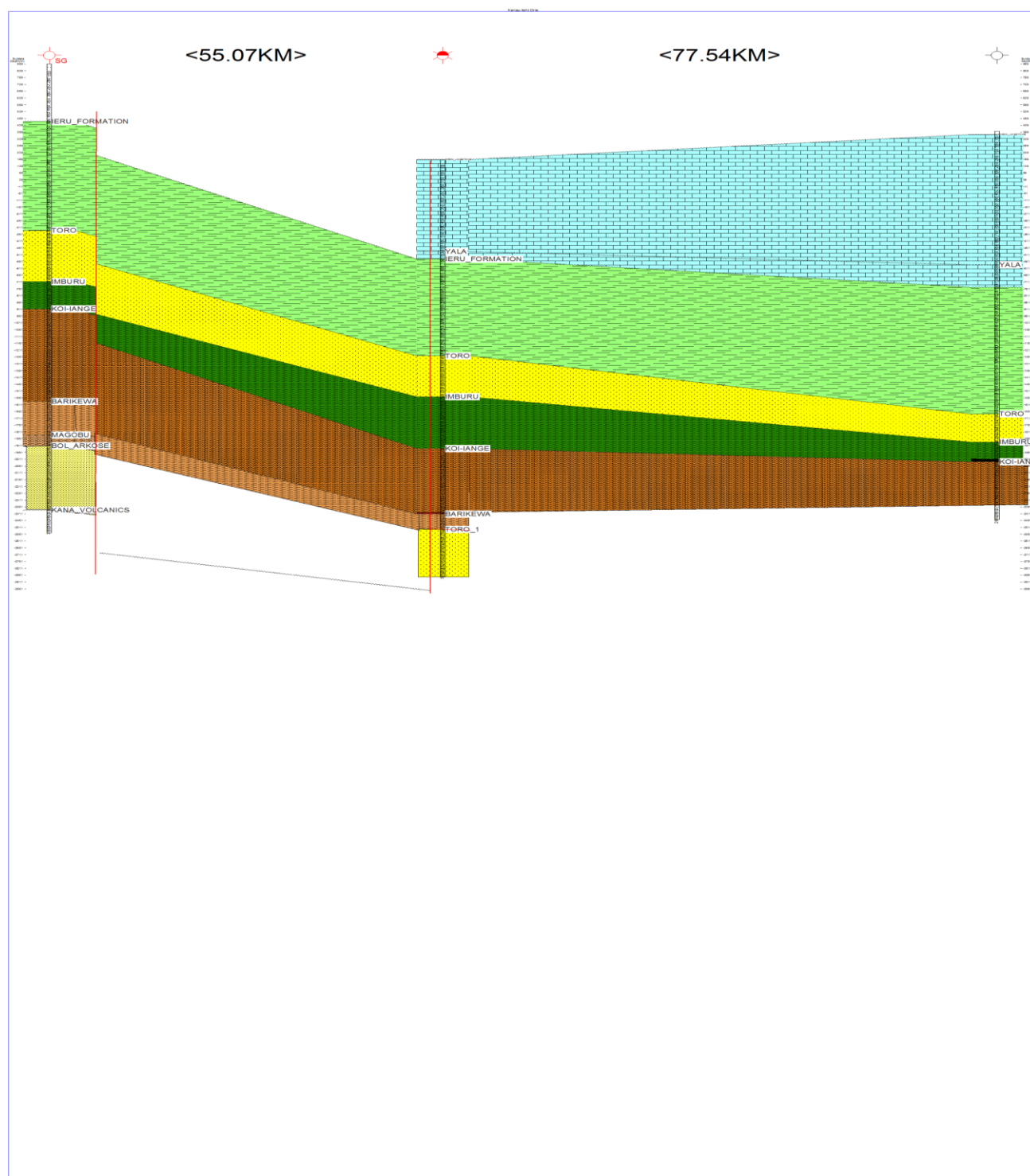


Figure 30: Structural subsea cross section between the wells Kanau – Iehi – Orie. Faults are represented in red. The geographical location for this cross section is shown in the map. Note the repetition of the Toro Sandstone in the central Iehi well. A thrust fault is recorded in this well on drilling logs.

Located towards the Western portion of The Papuan Basin are the Kiunga, Lake Murray 1, Lake Murray 2, and Morehead wells. These wells are dry holes with no observed hydrocarbon production. The cross section between each of these wells is depicted in Figure 31. Two major basement involved faults are represented between these four wells based on surface mapping conducted by the Commonwealth of Australia (Barndollar, 1993). The Jurassic units are intersected only in the Morehead well and the Kiunga well. The Toro and Imburu units are less than 50 meters thick in these two wells. Thick Eocene and Miocene carbonates overlay the Cretaceous Ieru Formation. The Kiunga well was drilled on a seismically detected faulted basement high. Drill tests of the Toro Sandstone in the Kiunga well detected salt water with minor gas shows. Mesozoic sands in the Lake Murray 1 well had low permeability with minor gas shows. Lake Murray 2 was drilled down flank of a basement high from Lake Murray 1. Fifty meters of the Toro Sandstone was intersected at a depth of 1,875 meters yielding no hydrocarbon production.

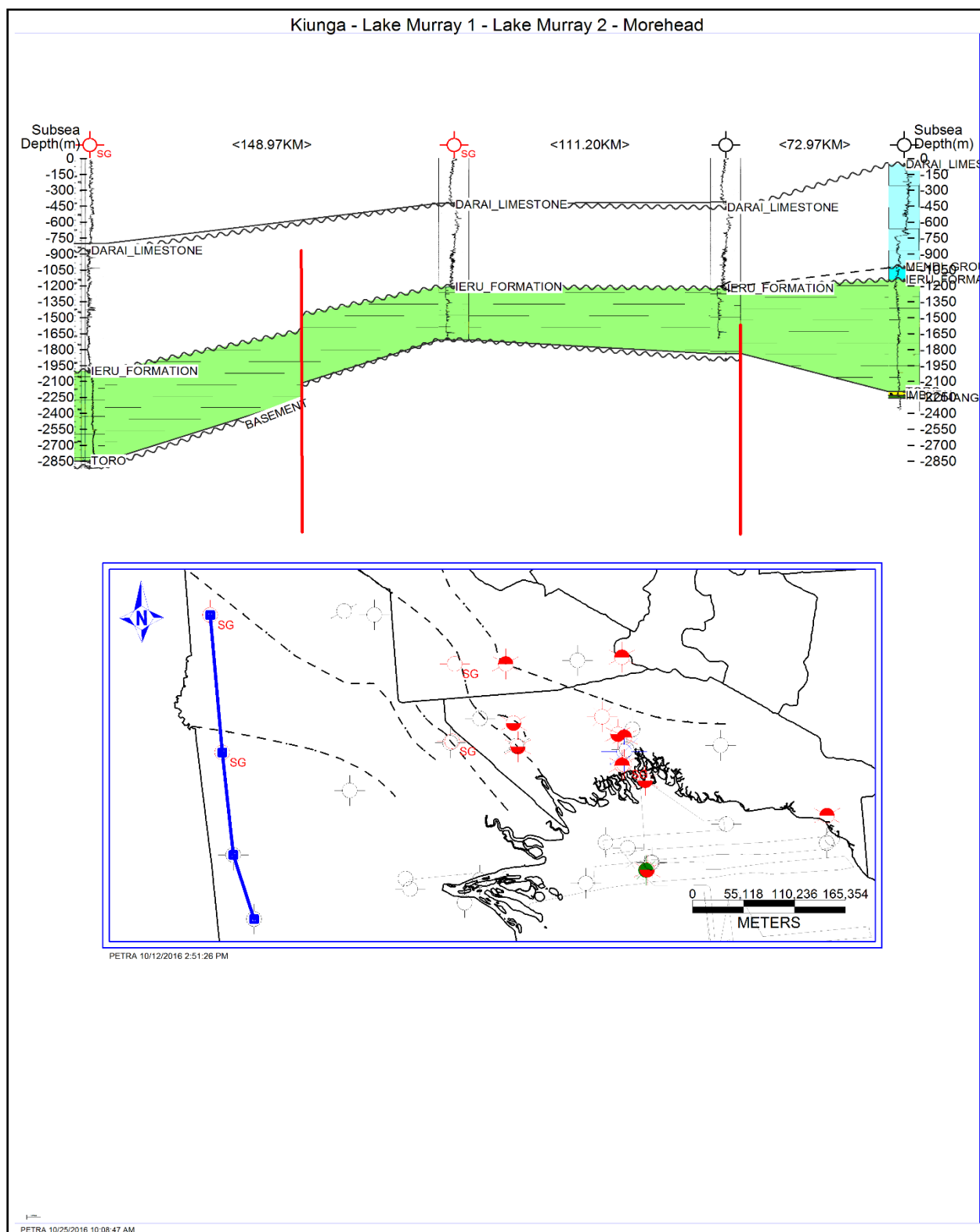


Figure 31: Structural cross section between Kiunga – Lake Murray 1 – Lake Murray 2 – and Morehead wells. Red lines represent fault location. The geographical location for this cross section is shown in the map.

The cross section between the Orie, Darai, and Aramia wells depicts the subsurface structure and stratigraphy (Fig. 32). This cross section ranges from SW to NE, and is 283.35 kilometers in length. Several major fault systems are intersected across Figure 32. The Toro and Imburu Formations are present in each well at various depths less than 2,000 meters. No significant hydrocarbon discoveries were made in any of these wells. The Orie well was drilled to test a surface mapped anticline. Poorly developed Toro Sandstone reservoirs were encountered in the Orie well. The Darai well encountered good Toro Sandstone reservoirs; however, the reservoirs were partially flushed according to drilling logs. In Figure 32, the overlying Darai Limestone unit is present in all three wells. The Eocene Yala Limestone is located only in the Orie well.

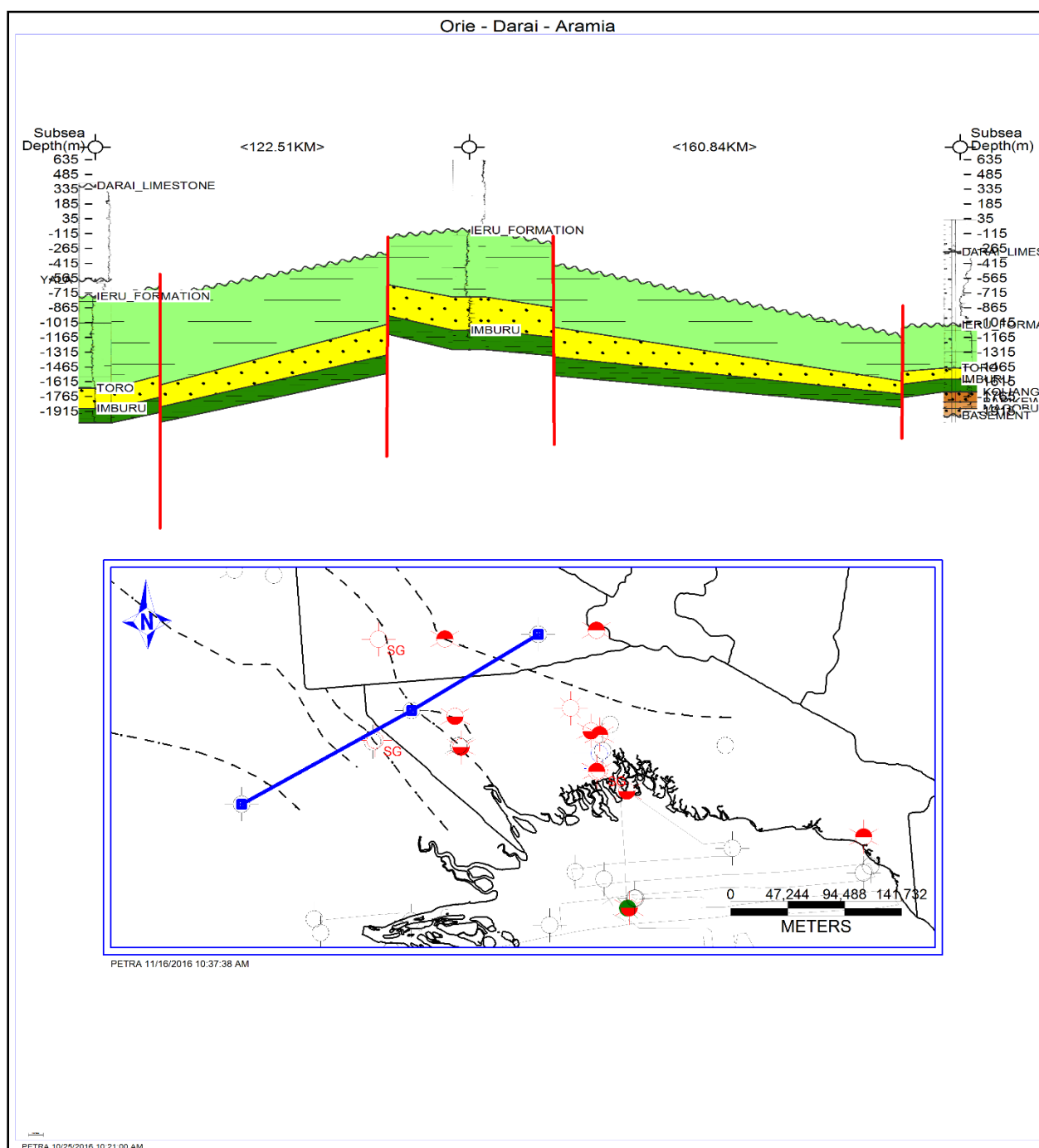


Figure 32: Structural cross section between Orie – Dara – Aramia. Dashed lines represent Jurassic fault systems. The location of this cross section is represented by the blue line in the location map.

Figure 33 shows a structural cross section constructed between the Darai and Barikewa wells. This cross-section crosses over an identified normal fault. The Barikewa well lies on the downthrown block with a reverse fault located slightly east of the well location. Jurassic source rocks, like the Imburu and Barikewa, are present in each of the wells. A displacement of ~700 meters is observed across the normal fault (Figure 33). The Imburu Formation is present at a depth range of 1,700 to 2,100 meters, and the Barikewa Formation is at a depth of 2,700 to 3,900 meters. The Barikewa Formation was not intersected in the Darai well.

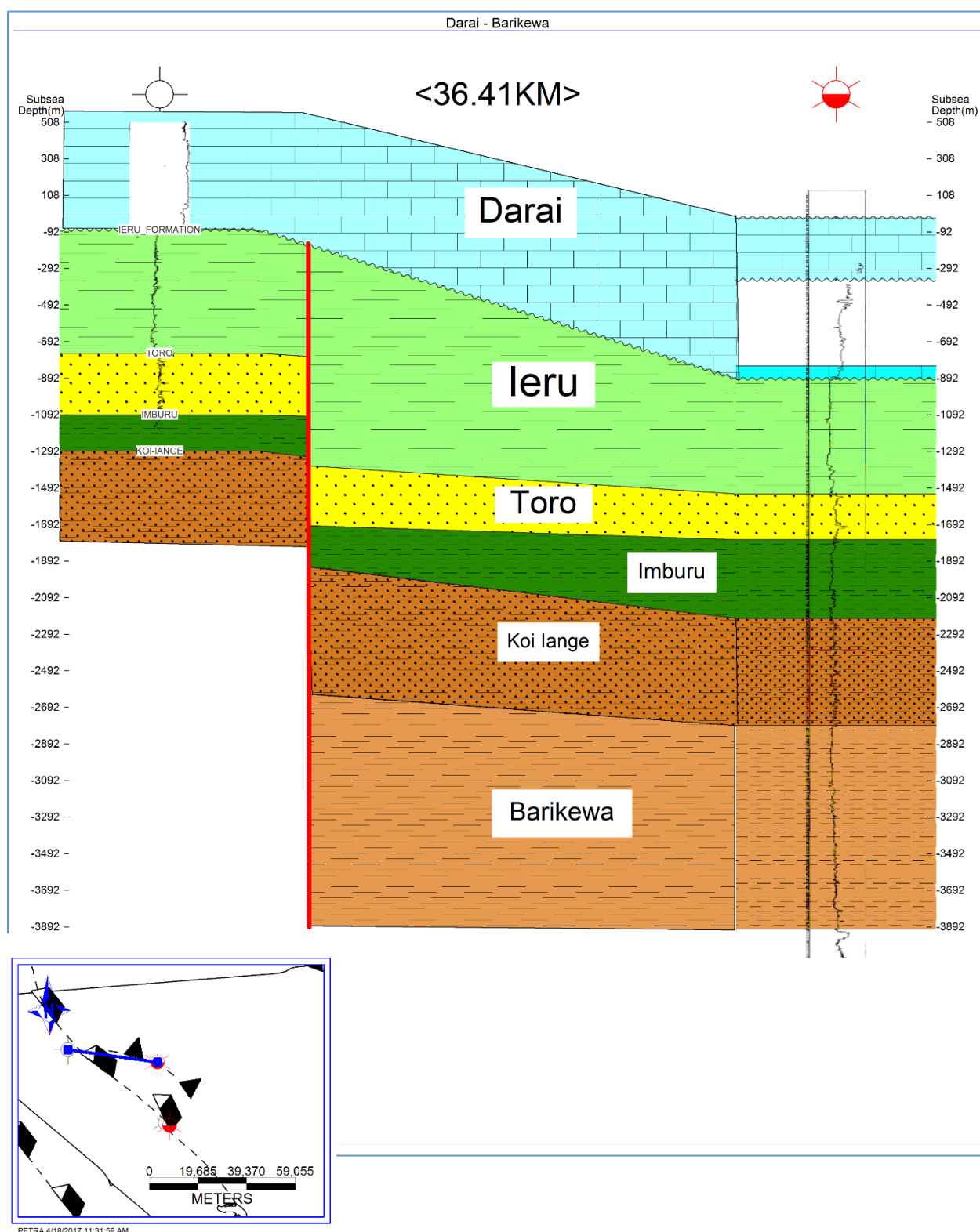


Figure 33: Structural cross section between Darai and Barikewa. Red lines represent Jurassic fault systems. The location of this cross section is represented by the blue line in the location map.

A cross section between Komewu 2, Omati 1, and Muabu is shown below in Figure 34. Faults in this cross section are represented as vertical red lines due to the unknown orientation of the faults. Figure 34 is orientated West to East along the Southern portion of the onshore Papuan Basin. This cross section is situated across two structurally identified basement involved normal faults.

The well Komewu 2 is drilled on the upthrown portion of one of the normal faults. Komewu 2 contains minor gas shows. Omati 1 is situated in the deeper portion of the Papuan Basin. Omati 1 has gas and condensate production that has been generated from the Jurassic and Cretaceous Toro Sandstone at 3,670 meters. Omati 1 was drilled to a total depth of 4,734.5 meters.

Carbonate units in Omati 1 contain varying lithological characteristics. The Darai Limestone is a fossiliferous, porous, calcareous limestone with partially dolomitized zones. The Puri Limestone in this well is calcareous and dense with partially dolomitized zones with some cherty beds. The only hydrocarbon production observed in any of the carbonate units in Figure 34 is located within the Muabu well. The Muabu well was drilled to a total depth of 3,666.3 meters.

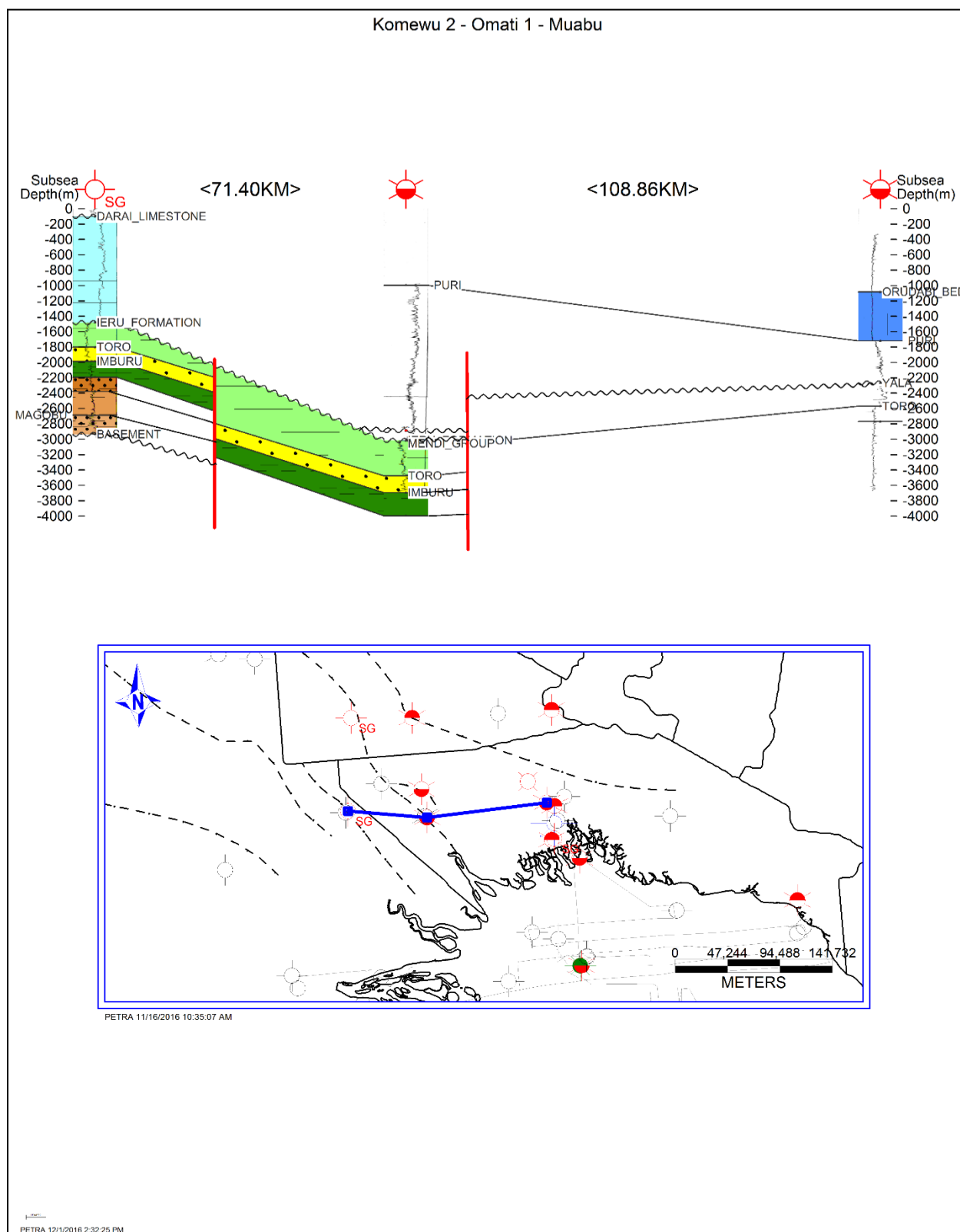


Figure 34: Structural cross section between Komewu 2 – Omati 1 – and Muabu. Red lines in the cross section represent interpreted fault structures. Fault lines are represented vertically with unknown orientations.

A cross section between Kiunga – Mananda – Iehi – and Bwata was constructed in Figure 35. The location of structural faults was interpreted along the cross section line. The Imburu and Barikewa source rock depth vary across the cross section. However, only the Mananda and Iehi wells intersected these source units. A thrust fault was intersected in the Iehi well with repeated section of the Cretaceous Toro Sandstone

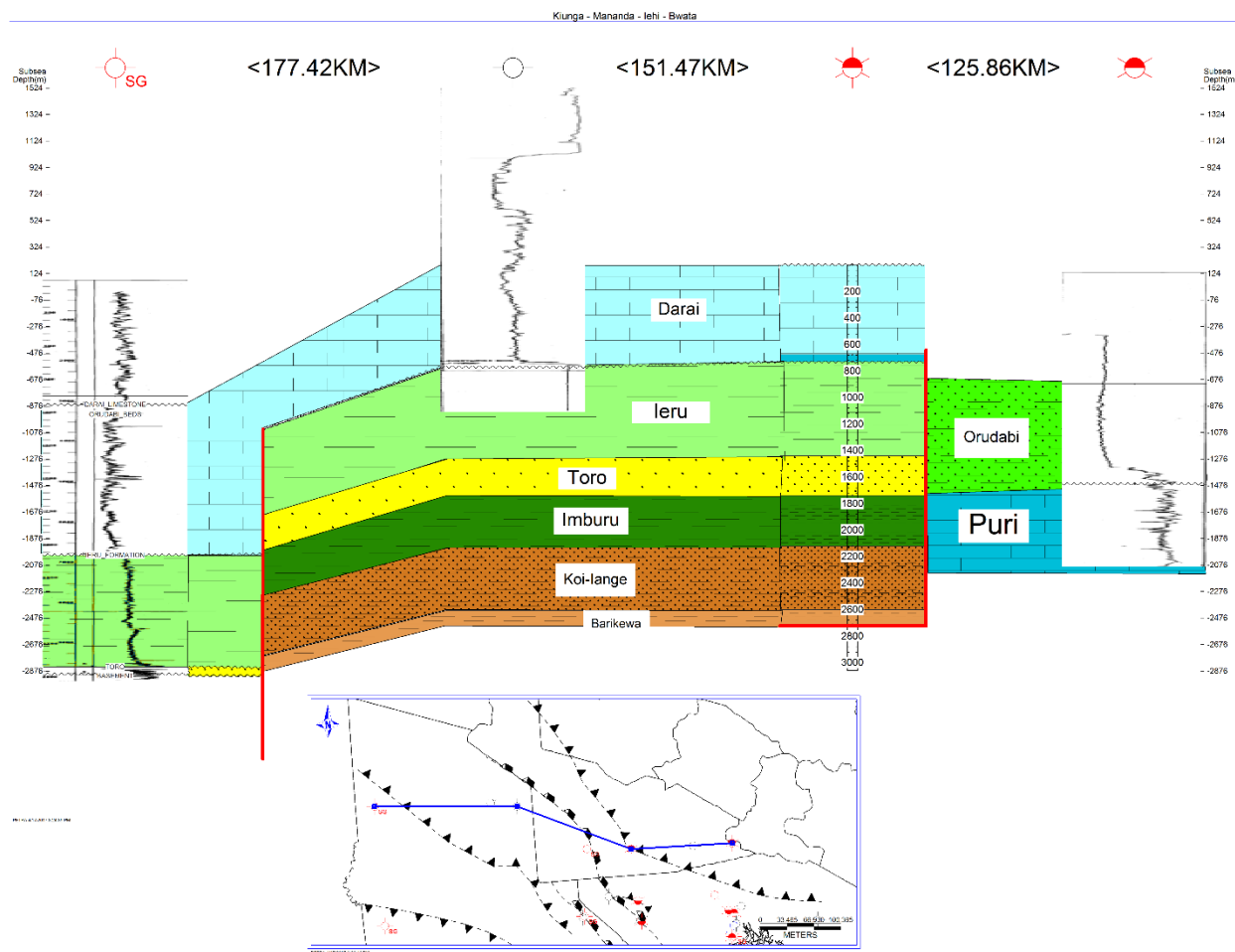


Figure 35: Structural cross section between Kiunga – Mananda – Iehi – Bwata. Red lines in the cross section represent interpreted fault structures. Fault lines are represented vertically with unknown orientations. The location of the cross section is represented in the location map.

The cross section between Mananda, Kanau, and Darai was constructed in Figure 36. No faults were interpreted between this cross section. The cross section lies on the upthrown block of a normal fault system identified in the Papuan Basin. The Mananda well terminates before reaching the Cretaceous reservoir rock.

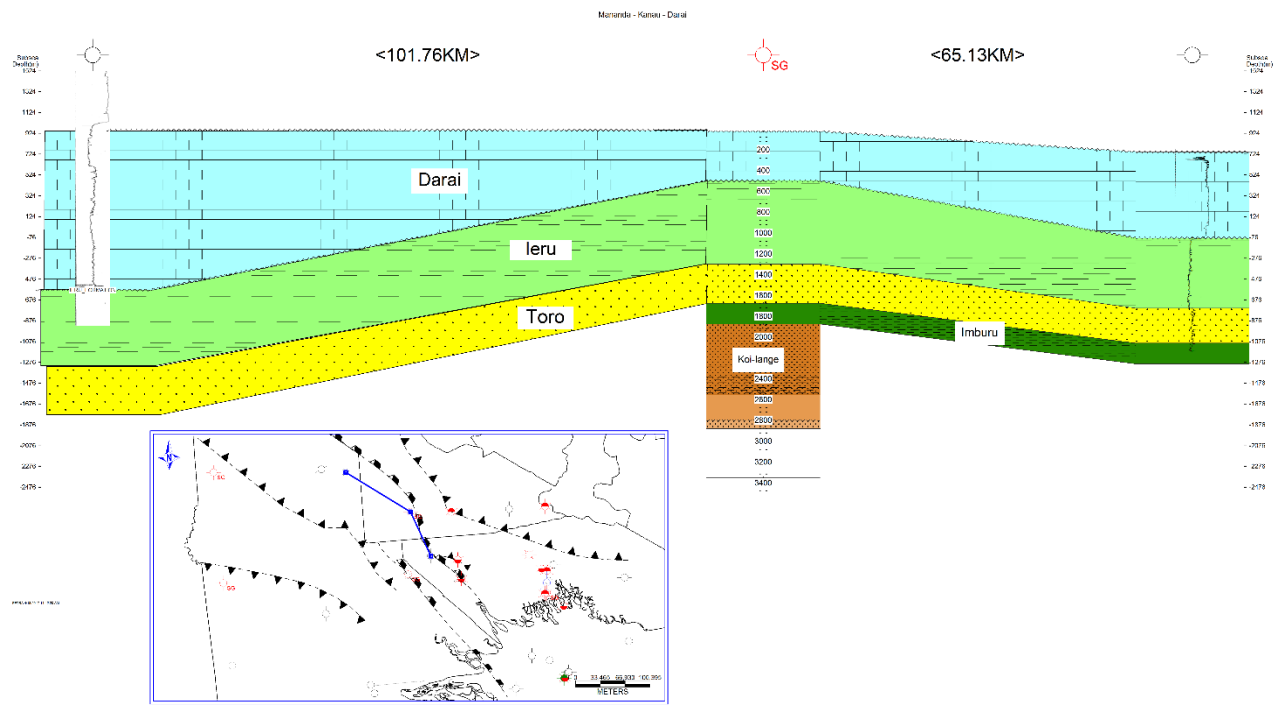


Figure 36: Structural cross section between Mananda – Kanau – Darai. The location of the cross section is represented in the location map. This cross section lies on the upthrown block of a normal fault system.

A structural cross section between Barikewa, Uramu, Puri, and Pasca A1 is shown in Figure 37. The location of two thrust faults are interpreted based on the subsurface structural cross section. The Imburu source rock is present in the Barikewa and Uramu wells. The connection to Pasca A1 cannot be accurately interpreted with the limited well control.

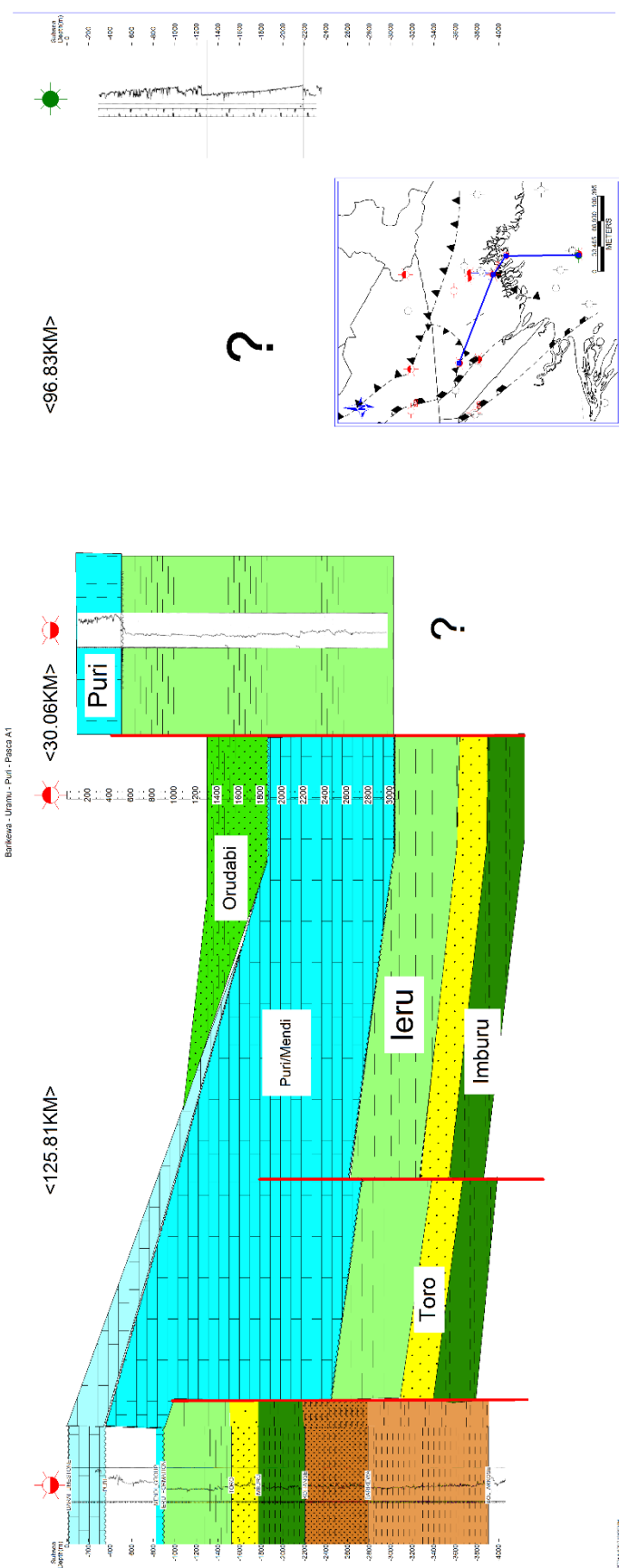


Figure 37: Structural cross section between Barikewa – Uramu – Puri – Pasca A1. The location of the cross section is represented in the location map. Fault locations are represented by vertical red lines with unknown orientations.

Figure 38 shows a cross section between Muabu, Uramu, and Dibiri. This cross section is located on the southern portion of the onshore Papuan Basin, and trends North to South. The Toro is present in the Muabu well, and pinches out towards the South. The lower Jurassic units were not intersected in this cross section.

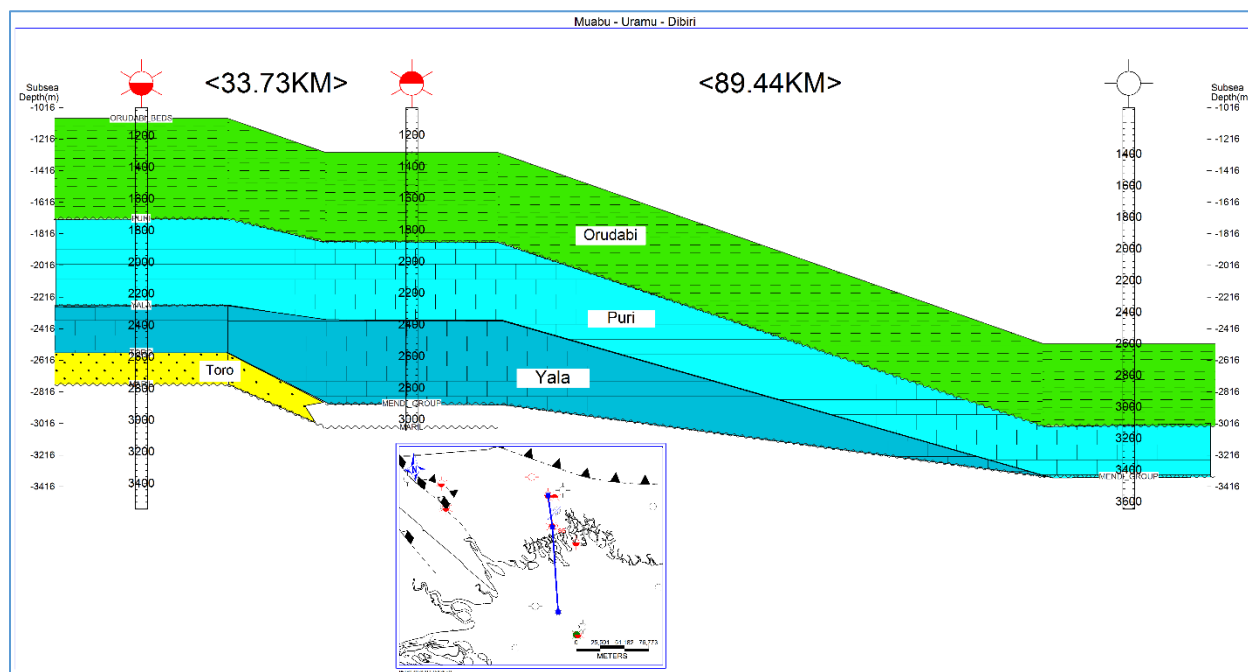


Figure 38: Structural cross section between Muabu – Uramu - Dibiri. The location of this cross section is shown in the location map.

A cross section between Morehead, Mutare, Wuroi, and Kusa is shown in Figure 39. This cross section extends West to East across the southern portion of the Papuan Basin. The extension of the fault system in the onshore Papuan Basin is interpreted to extend into the offshore shelf of the Gulf of Papua. A basement high is observed in the Mutare well. Jurassic and Cretaceous units in all the wells thin out towards the southern portion of the onshore Papuan Basin.

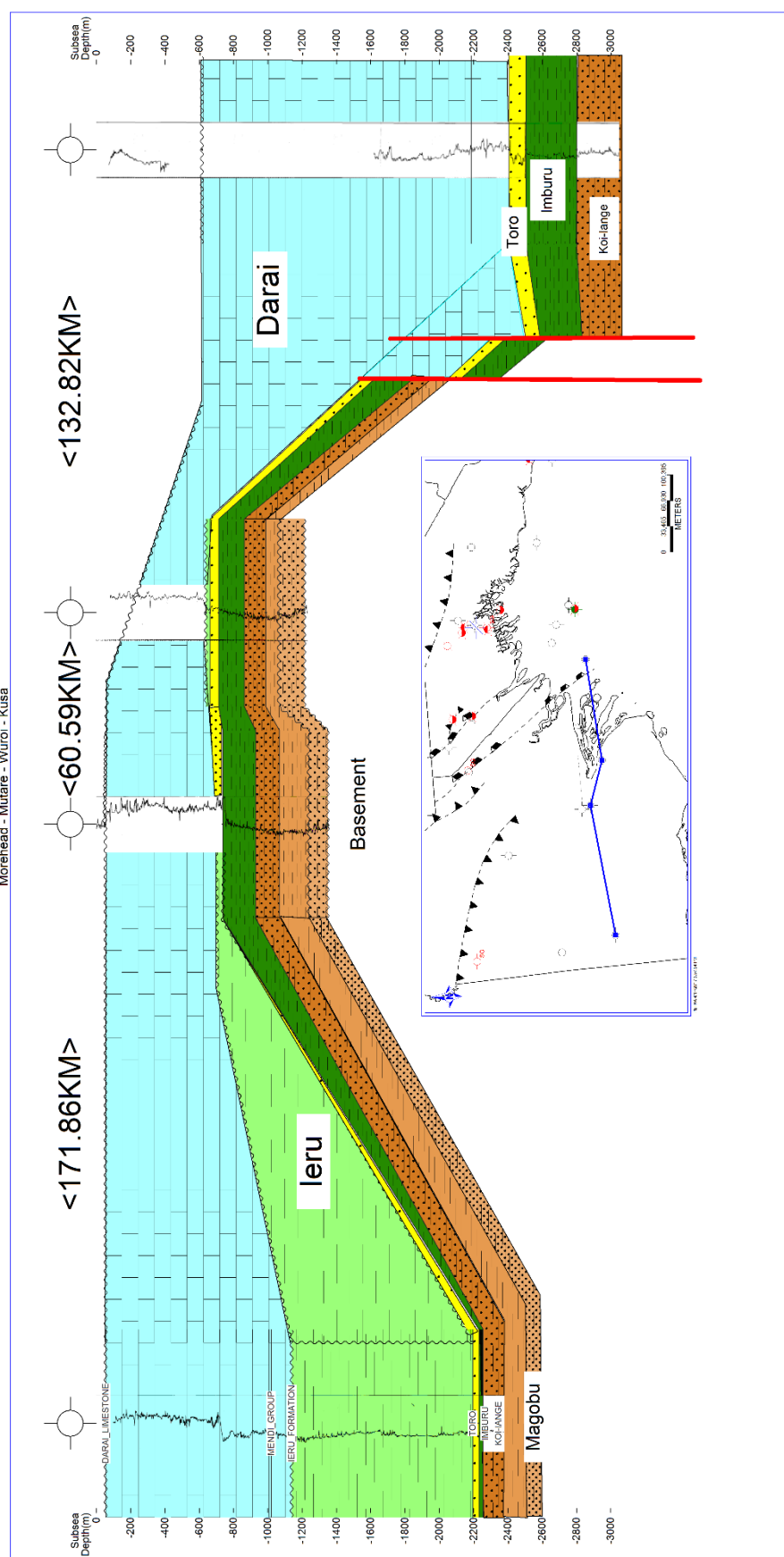


Figure 39: Structural cross section between Morehead – Mutare – Wuroi – Kusa. The location of the cross section is represented in the location map. Fault locations are represented by vertical red lines with unknown orientations. The location of the cross section is shown in the location map.

Gulf of Papua Extensional Faulting and Reef Structures

Limited Seismic data was available for onshore interpretation. Figure 40 shows an interpreted seismic line of the Pasca A3 well as a potential hydrocarbon play. The seismic lines for Pasca were reprocessed in 1979. Currently, no digitized data exists in the Bogue Hunt Database for 3D correlation. A location map using Petra is provided for a geographic reference.

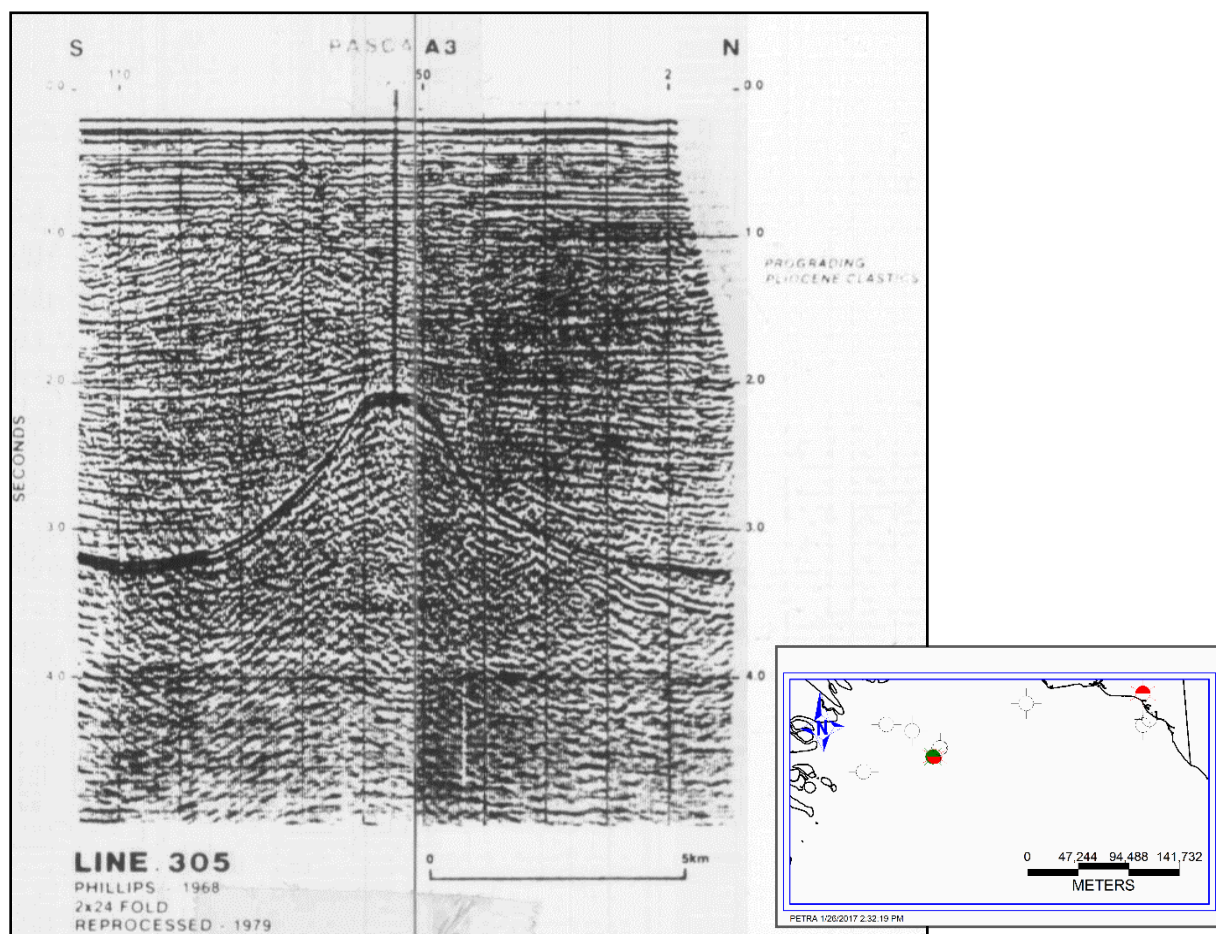


Figure 40: 1979 reprocessed seismic line of the Pasca A3 well. Interpretation of one of the Pasca Reef's is shown. The location is represented by the green dot on the location map (from the L. Bogue Hunt Database).

Figure 41 shows a seismic line and the approximate location map. The exact location of this line is unknown; however, the general location is based off the line number and name. This figure shows an interpretation of subsurface structure with a series of extensional faulting.

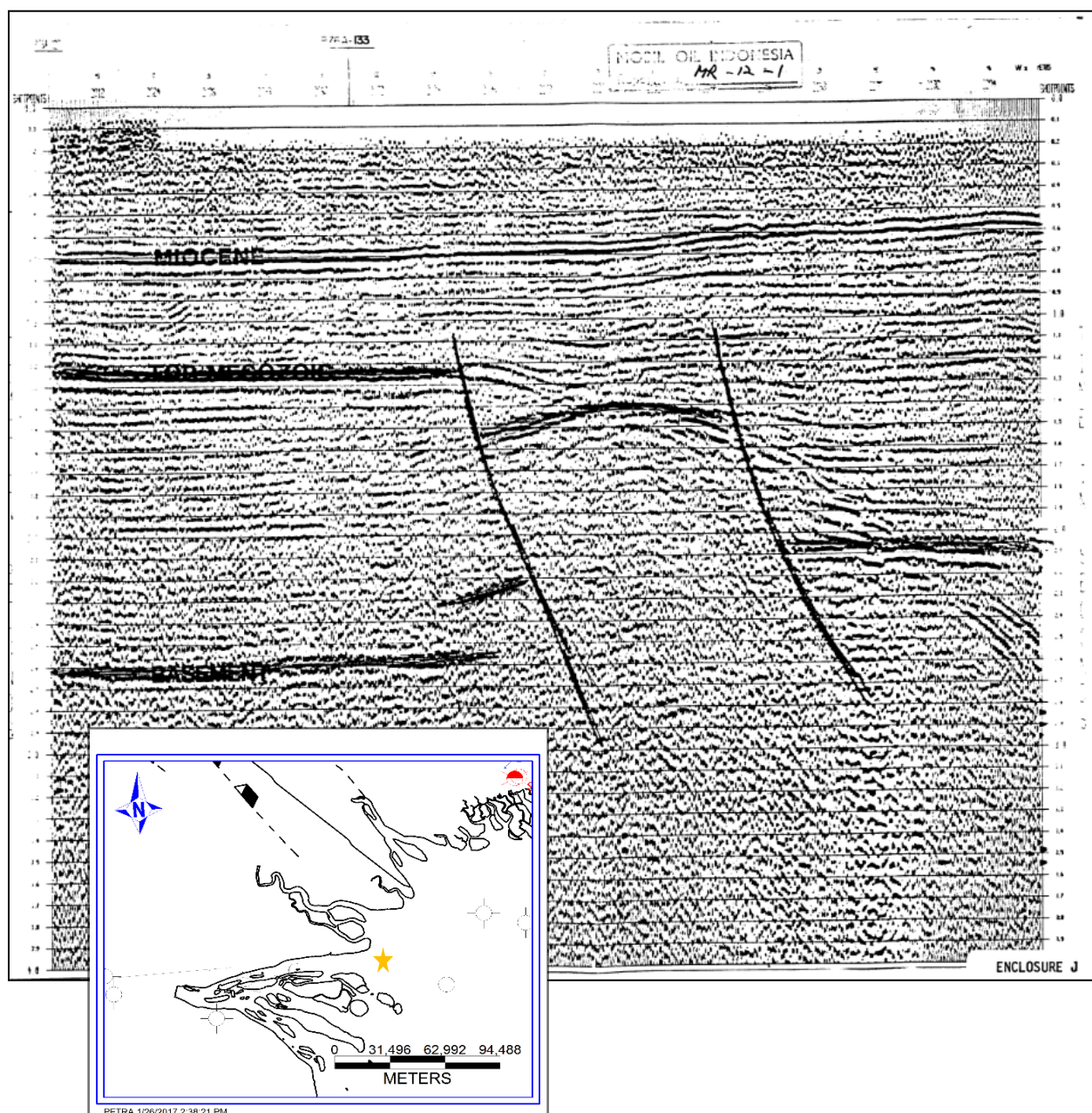


Figure 41: This figure shows extensional tectonics with a series of normal faults extending into the offshore Gulf of Papua. The approximate location is marked by the orange star on the location map (From the L. Bogue Hunt Database).

DISCUSSION

A limited understanding of the structural and stratigraphic controls on the basin has hindered current exploration progress. A constructed depth to basement map (Fig. 11) indicates that the majority of producing wells are located within the deeper parts of the basin. Drilling logs suggest that the Jurassic-Cretaceous units in the Papuan Basin have a limited production potential at depths shallower than 2,000 meters due to the lack of production in these wells. This depth is calculated using limited data; however, this depth may provide one plausible explanation for the numerous dry holes in the Papuan Basin. Graben structures in the basin have been able to reach the necessary depth for hydrocarbon generation (Fig. 24, 26, 29, 34). However, migration of oil and gas, particularly in zones affected by complex compressional tectonics, may have migrated hydrocarbons to shallower depths. Evidence of this can be seen in the Iehi Well (Fig. 30), by the lack of production in the repeated Jurassic units at the base of the well. Limited core data throughout the basin places a reliance on wireline log data. In most cases, this data is almost used exclusively to infer depositional, lithological, and structural characteristics. Well-log data and previous literature in the basin (Barndollar 1993; Buchanan and Warburton 1996; Gordon et al. 2000; McConachie and Lanzilli, 2000), suggests that the Lower Jurassic Imburu Formation is one of the major hydrocarbon source units for the basin (Figure 21). The Imburu Formation consists of a grey to dark grey, fine grained mudstone. Bioturbated argillaceous laminae and glauconitic peloids are also common within the Imburu (Boult, 1993). Drill logs from the Hunt Database suggest that deeper Jurassic mudstones, like the Barikewa (Fig. 16), may also be a potential source unit in deeper parts of the basin. However, very few wells in the basin intersect this Formation.

Above the Jurassic Mudstones lies a Late Jurassic to Early Cretaceous Sandstone reservoir named the Toro Sandstone. Currently, the Toro Sandstone is a major target Formation for oil and gas exploration in the Eastern Papuan Fold Belt (Gordon, Huizinga and Sublette, 2000). Wells located in the Papuan Basin show the Toro Formation as a promising reservoir. However, lateral differences in argillaceous content may impact reservoir quality and production potential from location to location (Hirst and Price, 1996). Detailed well and lithological testing must be completed to evaluate the reservoir potential of this unit at various locations.

Above the Toro reservoir lies a potential seal rock for hydrocarbon systems in the Papuan Basin. The Ieru Formation is a late Berriasian glauconitic siltstone, with interbedded mudstones, and argillaceous sandstones. This unit represents an overall transgression after deposition of the Toro Sandstone. The Ieru is inferred to have deposited in a shelf environment (Phelps and Denison, 1993). The extent of the Ieru is modeled in Figure 26. This study identified the top of the Ieru in constructed cross sections as an unconformity. The time gap between the Ieru and the overlying carbonates are represented in Figure 7. The 3D model of the Ieru (Fig. 25) shows a continuous abundant unit across the basin. Barndollar (1993) has shown that the Ieru seal integrity was well maintained in the Iamara-1 well after undergoing erosion and folding. This suggests that the Ieru seal is capable of trapping hydrocarbons while undergoing intense deformation due to regional tectonic forces. Drill logs throughout the basin show thick correlative sequences of the Ieru. Evidence for oil and gas migration during regional tectonic pulses is well documented through previous literature throughout the Papuan basin (Home et al. 1990; Barndollar 1993; Waples and Wulff, 1996). As a result of deformation and folding, hydrocarbon accumulation in heavily folded regions is highly plausible. However, dry test wells

indicate that not every structurally closed trap contains hydrocarbon accumulations. Thus, it is important to fully understand the timing of fluid migration within the basin.

Hydrocarbon Trap Modeling: Structural Cross Sections and PETRA Modeling

Various cross sections were modeled across the Papuan Basin during this study. With the absence of abundant well log data, interpretations between wells have proven difficult. Figure 34 shows a constructed cross section across the Jurassic sourced rift play (Fig. 3). Thick skinned deformation is identified within this rift complex, and is a common structural feature across the Papuan Basin. The Omati 1 well lies within an identified rift zone where siliciclastic deposition took place during the Early Jurassic. Graben features and basement lows provided the necessary depth for hydrocarbon generation. Future identification of Horst and Graben structures within the Papuan Basin may be potential target locations for future commercial development. Another constructed cross section, with a large normal fault between the Barikewa and Omati 1 faults, is represented in Figure 29. This figure displays a North to South trending cross section. The normal fault between the Barikewa and Omati wells has a downward displacement of approximately 1,875 meters. Drill logs from both wells in this cross section (Fig. 29), show extractable gas and brine from the Toro and Imburu Formations. Another modeled cross section that trends from Northeast to Southwest in the Papuan Basin is shown in Figure 32. Various compressional and extensional faults are interpreted between the Orie, Darai, and Aramia wells. However, without detailed well control, the orientation of each of these faults is unknown in the subsurface. Overall, these 3 wells are identified as dry hole wells with no hydrocarbon production. In each of these wells, the Jurassic and Cretaceous source units are at a relatively

shallow depth with no structural trap. No graben or basement low at a depth greater than 2,000 meters is present around these locations. As a result, these wells remain dry due to a lack of a generative source. A comprehensive dry hole analysis was constructed for each of the wells in the Papuan Basin in Appendix A.

Jurassic Sourced Rift Play

Basinal rifting has led to development of a series of Horst and Graben structures in the Southwest portion of the basin (Fig. 3). The Jurassic rift play strikes NW to SE, and extends into the offshore Gulf of Papua. This study has shown evidence of this rift systems extension into the offshore (Fig. 41). The modeled depth to basement top indicates that the South Central portion of the onshore basin contains the thickest sedimentary sequences (Fig. 9). John, (1970), noted that at least 7,000 meters of Mesozoic sediments were deposited between the Aure Trough and West Irian. Maximum development of sedimentation took place in the Southern Highlands area (John, 1970). In this study, a strong correlation has been observed in the Papuan Basin between sediment thickness and hydrocarbon productivity for various wells (Fig. 11). The constructed structural contour map of the depth to basement rock shows the majority of productive wells are located in the deepest portion of the basin. This boundary shows the deepening trend of overlying siliciclastic material throughout the Papuan basin. As a result, we would expect greater source potential in this location (Fig. 11). The illustrated well symbols (Table 1) on Figure 11, shows seven producing wells at depths greater than 2,000 meters. Each of these wells are located in close proximity to an identified graben. Due to an over-mature marine sourcing for hydrocarbons, the basin tends to generate more gas than oil (Gordon, Huizinga and Sublette, 2000). As a comparison, the Papuan Fold Belt to the East can mature organic kerogen's

deposited post Jurassic, due to thicker sedimentary sequences than those found in the Papuan Basin.

Rift structures in the Papuan Basin are identified zones in this study where hydrocarbon generation is possible within Jurassic units. Cross sections modeled across the basin illustrate these rift structures (Fig. 29, 30, 34). However, due to limited data, various trap models cannot be accurately identified. Downward displacement of Jurassic and Cretaceous source rocks during rifting resulted in the generation and accumulation of hydrocarbons following structural closure (Gordon, Huizinga and Sublette, 2000). Graben structures (Fig. 29) may represent important locations for hydrocarbon generation. Current exploration of major rift zones has primarily taken place in the Fly River Area in Western Papua (Fig. 6). The Magobu Island No. 1 well is located on the Southwestern flank of the Papuan Basin. This location sits on an identified basement high (Fig. 6), where Tertiary and Mesozoic units pinch out towards the South. Only minor traces of hydrocarbons have been encountered in this area. According to drilling reports, large anticlinal structures, identified from seismic, were the primary target of Magobu Island No. 1 well. Conybeare and Jessop (1972), postulated that the anticlinal trend coincided with an intra-Mesozoic strand line developing into large lenticular sand units (Conybeare and Jessop, 1972). The Lower Cretaceous Toro Sandstone in Magobu Island No. 1 is present at a depth of 1,300 meters (Fig. 24). While structural closure of this system may have taken place, the system did not enter the oil/gas window due to the shallow depth of the Imburu source rock. However, stratigraphically this system has all the necessary requirements for hydrocarbon accumulation. This study averaged production depths in wells across the Papuan Basin, and found an average production depth of 2,054 meters. Ahmed et al. (2012) recorded oil samples from 12 wells in the Papuan Basin. Using data gathered by Ahmed et al. (2012), an average depth of 2,200 meters

was calculated (Volk et al. 2005; Ahmed et al. 2012). These findings coincide with depth observations observed in this study, and provide a plausible explanation for the productive well trend in the deeper parts of the basin.

Triassic basement involved grabens, like those observed in Figure 29, offer the best hydrocarbon production potential in the marine and slope facies of Jurassic sediments (Barndollar, 1993). Large graben complexes can be found in the southwestern onshore Papuan Basin that developed during periods of rifting (Fig. 29). The cross section (Fig. 32) shows the structural change across the basin as a result of regional rifting. A basement involved normal fault is interpreted to lie between the wells Komewu 2 and Omati 1. This normal fault is an extension of the Aramia Graben Complex (Fig. 6), which extends into the offshore Gulf of Papua (Fig. 41). This study indicates through drilling logs that roughly 500 meters of downward displacement is recorded in this normal fault system. The Jurassic Imburu Formation reaches a maximum depth of approximately 3,500 meters at the base of this graben (Fig. 22). Drilling logs indicate shows of extractable oil; however, exact values are unknown. Hydrocarbons generated within this graben will have migrated up the fault plane into overlying traps (Fig. 42). The presence of extractable oil within this graben (Fig. 22), suggests incomplete fluid migration. A poor understanding of oil migration throughout the Papuan Basin may explain why this region is still a frontier basin.

Jurassic Sourced Thrust Play

In addition to rifting, two main phases of uplift and erosion have been documented in the Papuan Basin (Earnshaw et al. 1993). These two compressional phases have trapped hydrocarbons that accumulated deep within the Papuan Basin. Jurassic sourced thrust plays are

found along the Northwestern portion of the onshore basin (Fig. 3). This thrust play strikes NW-SE, and intersects several drilled test wells in the basin. The first phase of uplift took place during the Late Cretaceous as a response to rifting of the Coral Sea (Davies and Smith, 1971; Earnshaw et al. 1993). The second rifting phase took place during the Pliocene from collisional tectonics (Earnshaw et al. 1993). Hill et al. (1991) suggested that oil generation and migration took place during the Late Cretaceous within thick Mesozoic sequences (Earnshaw et al. 1993). Gordon et al. (2000) suggested that oil generation took place during two distinct phases; the Late Cretaceous, and Late Cenozoic. The first phase would have taken place immediately following the structural closure of the Jurassic/Cretaceous hydrocarbon systems.

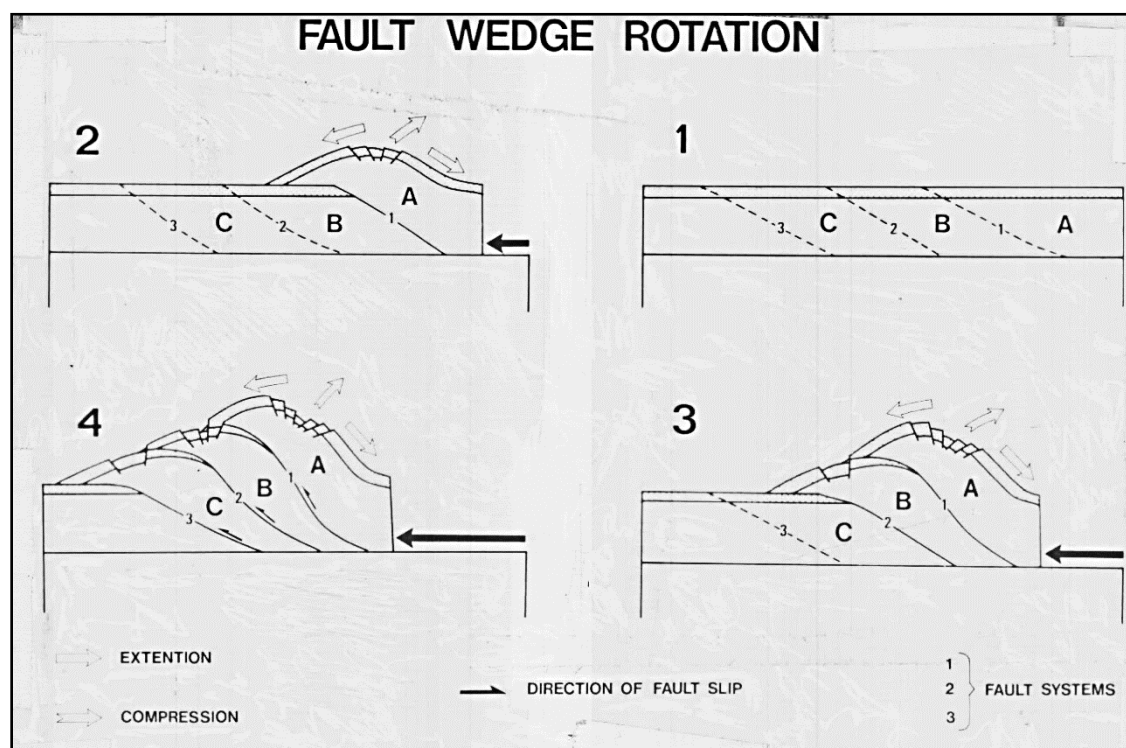


Figure 42: Diagram of Fault Wedge Rotation showing structural changes of rock units from extensional and compressional stresses. The development of anticlinal structures developed from folding and thrusting. These faulted anticlines represent the ideal locations for hydrocarbon trapping (from the L. Bogue Hunt database, modified after Gibbs, 2012.) 1) Units A, B, C were deposited horizontally (the sequential faulting order is represented by the dashed lines). 2) Initial compression results in the movement of fault block A. Extensional shedding takes place on the anticlinal structure. 3) A second compressive force thrusts units A and B along fault plane 2. Extensional shedding takes place in units A and B. 4) A third compressive force thrusts units A, B, and C along fault plane 3.

Thrust plays generate oil and gas that are trapped within anticlinal structures. These plays are located on the flanks of upthrown fault blocks, and form by a process referred as fault wedge rotation. Fault wedge rotation is present in these thrust faulted zones (Fig. 42), and forms as a response to compressional forces that take place regionally within the Papuan Basin. Initial compression induces thrust faulting of horizontally placed sedimentary units. As the thrust fault block is uplifted and folded, extensional shedding takes place on the hinge of these

anticlinal structures. Anticlines within the basin have been seismically mapped by various petroleum companies as potential prospects. Commercially drilled wells along this zone have shown promising results for reservoir development.

A major thrust fault has been identified in the Iehi Well (Fig. 30). Repeated Cretaceous and Jurassic sections were observed in this well from drilling logs. Dry gas was produced in the Iehi well between the depths of 1,439 and 1,473 meters. Faulting may have allowed for gas migration in this well. The repeated Toro Sandstone is measured at a depth of 2,650 meters (Fig. 30). The Cretaceous Ieru seal unit was not repeated in this well, and the thrust fault in the Iehi well is believed to be a reactivated normal fault due to compressional tectonics. Oil and gas accumulation within trap zones develop because of migration pathways generated by these fault planes. Reverse and thrust faulting within the Papuan Basin would have taken place after initial hydrocarbon generation within grabens. This scenario implies a deeper generation and maturation of oil in this part of the basin ($>2,000$ meters). Graben structures would have dropped down the Jurassic units to a deep enough depth to become thermally mature. Barikewa 1 (Fig. 29), a neighboring well drilled to a total depth of 4,233.7 meters, intersects the Lower Jurassic Bol Arkose Sandstone at a depth of 4,050 meters. However, no hydrocarbons were observed at this depth during drilling. The Barikewa 1 well is one of the deepest drilled wells in the Papuan Basin, and sits within an identified graben (Fig. 29). The Barikewa 1 well terminates before reaching basement rock. Oil and gas migration from this depth may have been possible from pulses of compressional tectonics impacting this region. As a result, oil and gas would have migrated upwards towards structural anticlines, and productivity of this well may be limited by this migration event.

A modeled cross section trending north to south on the western portion of the foreland basin is represented in Figure 31. A structural basement high is located along the Kiunga 1, Lake Murray 1, and Lake Murray 2 wells. The Kiunga 1 well is located within the Jurassic Thrust Play (Fig. 3); however, only minor gas shows are recorded in Miocene carbonates. The Jurassic and Cretaceous units in this cross section thin out, and are present at a depth shallower than 2,000 meters. This depth is too shallow for any hydrocarbon maturation, and the Toro reservoir is not thick enough to support production. A modeled isopach map of the Toro demonstrating this trend is shown in Figure 21.

Tertiary Gas-Condensate Play

The final hydrocarbon play, shown in Figure 3, is a Tertiary gas – condensate play. This play is located in the central Gulf of Papua. Eocene and Miocene carbonates, such as the Darai limestones (Fig. 28), are target Formations for current hydrocarbon exploration. Miocene reef limestones in the Gulf of Papua were first discovered by seismic surveys conducted in the region by Phillips Petroleum (Durkee, 1990). Currently, the Pasca well is the only commercially producing offshore well. The Pasca Reef is intersected in this well at a depth of 2,200 meters. Over 1,000 barrels per day (BPD) are currently producing from the Miocene reef zone. Between the depths of 2,467- 2,502 meters is a commercially viable zone for gas production. An interpreted seismic line of the Pasca Reef complex is shown in Figure 40. Similar reef structures discovered in the Gulf of Papua have yet to be developed.

Similar drill tests in the Gulf of Papua have proven that large Miocene barrier reef trends exist. The Pasca Wells were drilled on an uplifted pre-Tertiary block, and represent a reef pinnacle located on a basement high (Durkee, 1990). Other drilled wells such as Borabi 1,

Uramu 1, are all drilled on identified reef trends. The entire Pasca Reef trend in the Gulf of Papua is seismically shown in Figure 40. This reef system is recognized worldwide as a major Northeast trending reef system (Durkee, 1990). The Borabi 1 well was the first drilled offshore well in 1967 (Jablonski et al. 2006). Borabi 1 initially tested this Miocene barrier reef; however, it was drilled off structure and lost drilling circulation (Jablonski et al. 2006). As a result, no production was recorded in this well. Enhancements in seismic imaging may allow for a productive Borabi 1 well if re-drilled. The second well drilled in this region was Uramu 1 in 1968. Uramu 1 encountered gas shows in the Uramu Reef Complex. The following test well, Uramu 1a, was abandoned during the drilling processes from high gas pressure within the Formation.

Identification of reef structures, like those seen in the Pasca wells, are difficult to identify without the use of updated seismic data. Several Pasca test wells were drilled since the initial seismic discovery. The Pasca 'A' reef is the current producing gas condensate reservoir with a bioherm of 381 meters (Jablonski et al. 2006). Little is known about the reservoir potential of this system due to a lack of core samples and porosity data. Studies into the Geophysical properties of the Pasca wells were conducted by Jablonski et al. (2006). Climactic conditions during the Early Miocene were conducive for reef growth in shallow marine waters. Outside of the Pasca reef, the Pandora reef in the southern Gulf of Papua has been identified in seismic as another potential play. The Pandora Reef is located approximately 200km offshore from Papua New Guinea (Carroll and Webb, 1996). This reef is primarily a gas producing reef with a gas reserve estimate of 1-2 Trillion Cubic Feet (TCF) (Carroll and Webb, 1996). However, the remote location of the Pandora Reef in the Southern Gulf of Papua means there are no effective hydrocarbon transportation methods currently in place. As a result, commercial development of a

pipeline in this area would require an average market price of US \$2.50 – 3.00 per MCF (Carroll and Webb, 1996). Offshore wells in the Gulf of Papua to this day remain highly lucrative.

CONCLUSION

1. The source rocks for hydrocarbon traps are Lower Jurassic Mudstones (Barikewa and Imburu). Reservoir rocks for these systems were identified as sandstone reservoirs within the Cretaceous Toro Sandstone. The final component to the system is the seal rock, which is the Cretaceous Ieru Siltstone/Mudstone.

2. This study suggests that the original zone for hydrocarbon production in the Papuan Basin took place within deep Graben structures or basement lows. Generated hydrocarbons within these structures migrated up fault planes into trap zones.

3. A depth of 2,000 meters is required for kerogens in the Papuan Basin to enter into the oil and gas window. Grabens and basement lows are the only places in the Papuan Basin where this depth can occur. The presence of gas suggests the hydrocarbon system is over-mature.

4. The Papuan Basin is considered a frontier basin with various unexplored areas. Tectonic pulses in this basin have led to oil and gas migration into complex structural traps that are yet to be discovered and tested.

5. Migration and maturity issues within the basin remain leading explanations for why the Papuan Basin is still considered a frontier basin with limited development.

FUTURE WORK

The use of computer modeling has greatly advanced our understanding of complex regions using limited data. However, computer modeling tends to make large assumptions over areas of missing data. With limited data in the Papuan Basin, more detailed observations must be conducted while exploring for hydrocarbons. For future work, I suggest gathering more core data and seismic data within the basin. With the aid of onshore seismic data, Geologists will be able to identify rift structures throughout the basin. The critical depth for hydrocarbon generation in this study should be used as a regional guideline for exploration. Throughout the offshore, I suggest conducting detailed studies of paleo-reefs. Specifically, I would look at the trap potential and look for similarities to the PASCA and Pandora reefs. Ultimately, with the addition of new data, existing computer modeling programs can be updated continuously to provide more detailed information.

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APPENDIX

Appendix A

Dry Hole Analysis

Borabi 1:

Drill logs show a loss of circulation at a depth of 1512 meters. Excellent reservoirs were recorded in the Borabi reef trend.

Cecilia 1:

This well was drilled to test a surface mapped thrust faulted anticline. This well was drilled to a depth of 3765.8 meters and failed to reach Cretaceous and Jurassic Sandstone reservoirs.

Darai 1:

This well was drilled to a depth of 2068.3 meters to test for a structural closure with a potential hydrocarbon trap. Partially flushed Toro Sandstone units were discovered with no structural closure. The lower Jurassic units were not encountered.

Iamara 1:

This well was drilled to a total depth of 1813.6 meters. Good Toro Sandstone reservoirs were encountered; however, no structural trap was identified.

Ini 1:

This well was drilled as part of the Uramu Reef Complex at a depth of 2734.1 meters. Intersection of the reef top resulted in salt water intrusion.

Iokea 1:

This well was drilled to test a diapiric anticlinal structure. Iokea 1 was drilled to a depth of 1475.2 meters, and only reached Pliocene units.

Ipigo 1:

This well was drilled to test a seismically postulated reef. The resulting well revealed a fault was responsible for the seismic anomaly.

Iviri 1:

This well was drilled to a depth of 3662.2 meters. Iviri was drilled to test the seismically defined Uramu Reef Complex. No hydrocarbons were encountered in this test well.

Kanau 1:

Kanau 1 was drilled to test a surface mapped structural anticline. The structural closure at depth was not proven.

Kapuri 1:

Drilled on an interpreted Biothermal Reef to a depth of 1698.3 meters. Salt water was encountered in reef carbonates.

Kiunga 1:

This well was drilled to test a faulted basement high for Jurassic and Cretaceous source rocks. Tests of the Toro Sandstone showed salt water with minor gas. This well was drilled to a depth of 3026 meters.

Komewu 1:

Komewu 1 was drilled on the upthrown fault block of the Komewu Fault. No stratigraphic or structural closure was present in this well. The Ieru seal was also missing from this well.

Kusa 1:

This well was drilled to a depth of 3433.6 meters to test a seismically identified anticline structure. Seismic indicates this well was drilled off structure.

Magobu Island 1:

This well was drilled on a basement high. Good Mesozoic Sandstone reservoirs were encountered with no structural closure.

Maiva 1:

Maiva 1 was drilled on a seismically identified anticline. No reservoir rocks were encountered in this well.

Morehead 1:

This well was drilled off of gravity and seismic reflection data. No closure over the faulted anticlinal structure was detected which resulted in no hydrocarbon accumulation.

Mutare 1:

Mutare 1 was drilled to a depth of 1419 meters. Toro reservoir sands were not encountered and were possibly eroded away.

Omati 2:

Abandoned well at a depth of 3316 meters.

Orie 1:

Poor development of the Toro Sandstone was found in this well.

Orokolo 1:

This well was drilled to a depth of 3657.3 meters. No Jurassic sand units were found in this well.

Wuroi 1:

No structural closure was observed in this well. Sandstone reservoirs were encountered.

Appendix B

Geographical well location and type.

Well Name	Latitude	Longitude	Well Type	Elevation (m)
BORABI 1	-8.104	144.2229	Gamma/Res	10
DARAI 1	-7.005322	143.283409	Gamma/Res	769
DIBIRI 1A	-8.1657084	144.4016587	Gamma/Res	90
IAMARA 1	-8.244	142.5619	SP/RES	11
INI 1	-7.3719	144.4404	SP/RES	73
IOKEA 1	-8.23346	146.11462	SP/RES	30
IPIGO 1	-7.1946	144.5241	SP/RES	9
IVIRI-1	-7.3554	144.463	SP/RES	6
KANAU 1	-6.546541	143.112595	SP/RES	171
KAPURI 1	-8.18218	146.84	SP/RES	10
KIUNGA 1	-6.0056099	141.1835485	Gamma/Res	74
KOMEWU 1	-7.1805	143.0242	Gamma/Res	27
KOMEWU 2	-7.1709	143.0411	SP/RES	38
KUSA 1	-8.422852	144.838288	Gamma/Res	14
LAKE MURRAY 1	-7.1004	141.1904	Gamma/Res	27
LAKE MURRAY 2	-7.91655	141.20184	Gamma/Res	38
MAGOBU ISLAND	-8.3147	143.1631	Gamma/Res	9
MAIVA 1	-8.2718	146.0536	SP/RES	10
ANCHOR CLAY	-9.262943	144.331	SP/RES	73
ARAMIA 1	-7.494547	142.180082	SP/RES	24
BORABI 1	-8.104	144.2229	Gamma/Res	10
PASCA A2	-8.362277	144.545399	Gamma/Res	10
PASCA C1	-8.304457	144.583114	Gamma/Res	10
PASCA C2	-8.3047	144.591	Gamma/Res	10
PASCA CS CONT	-8.3047	144.591	Gamma/Res	10
RARAKO Creek 1	-7.385	145.2448	caliper/res	81
TOVALA 1A	-8.0423	146.0845	Gamma/SP/Res	17
URAMU 1A	-7.48246	144.41406	GAMMA/RES	10
WANA 1	-7.2524	144.4516	SP/RES	7
WUROI 1	-8.4852	143.022	SP/RES	62

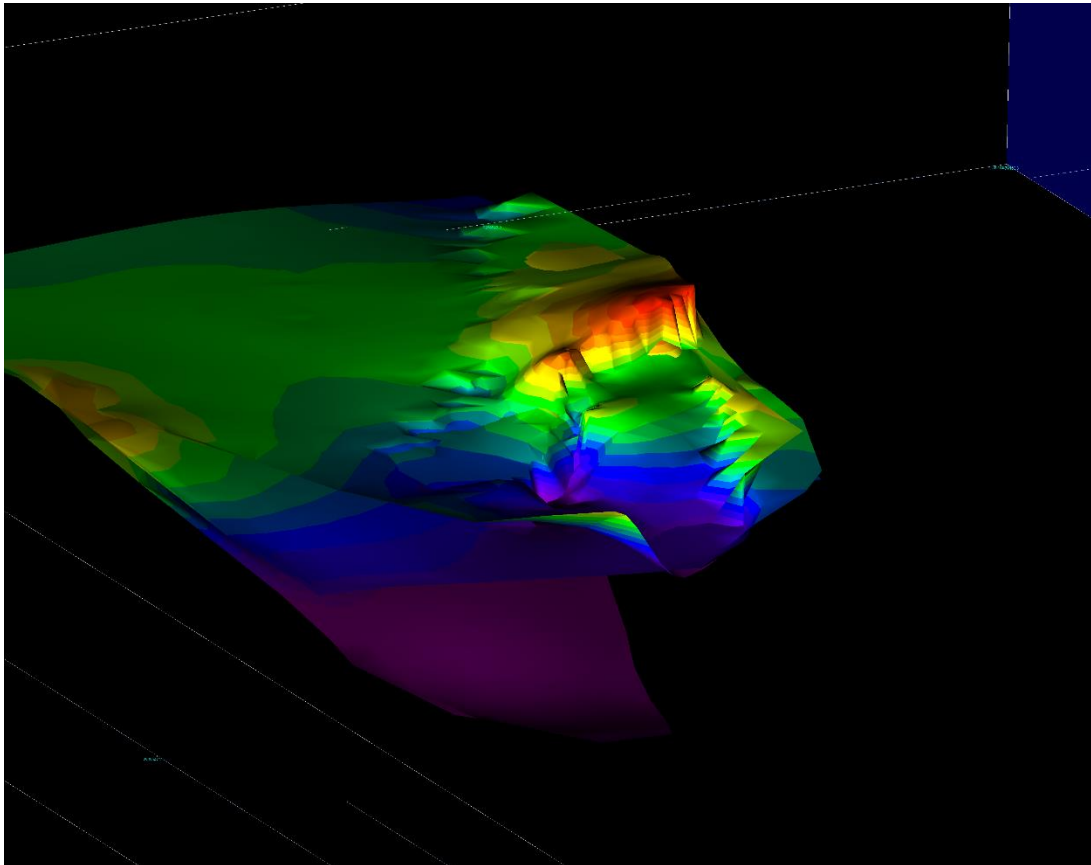
Appendix C

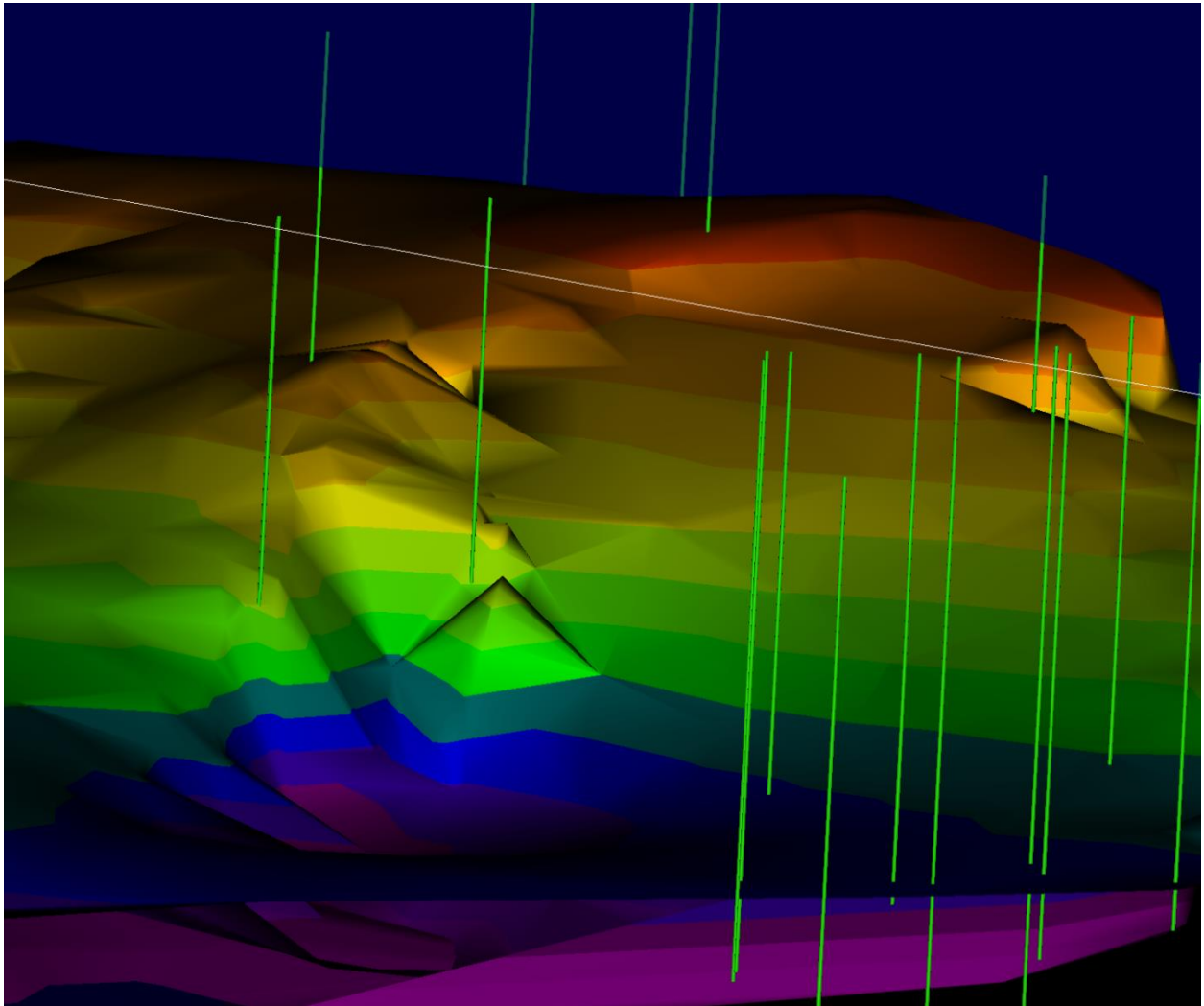
Well production amounts in the Papuan Basin.

Well Name	Production Amounts	Units		
Iehi 1	32	MMCFD		
Bwata	43	MMCFD		LEGEND
Barikewa	2.5	MMCFD		Condensate
Omati 1	Minor Oil Shows			Gas
Muabu	Minor			
Wana	Minor			
Uramu	24,000	MCFGPD		
Uramu	48	BPD		
Puri 1	8.06	MMCFD		
Pasca A1	15.12	MMCFD		
Pasca A1	1008	BPD		
Pasca A2	15.12	MMCFD		
Pasca A2	1115	BPD		

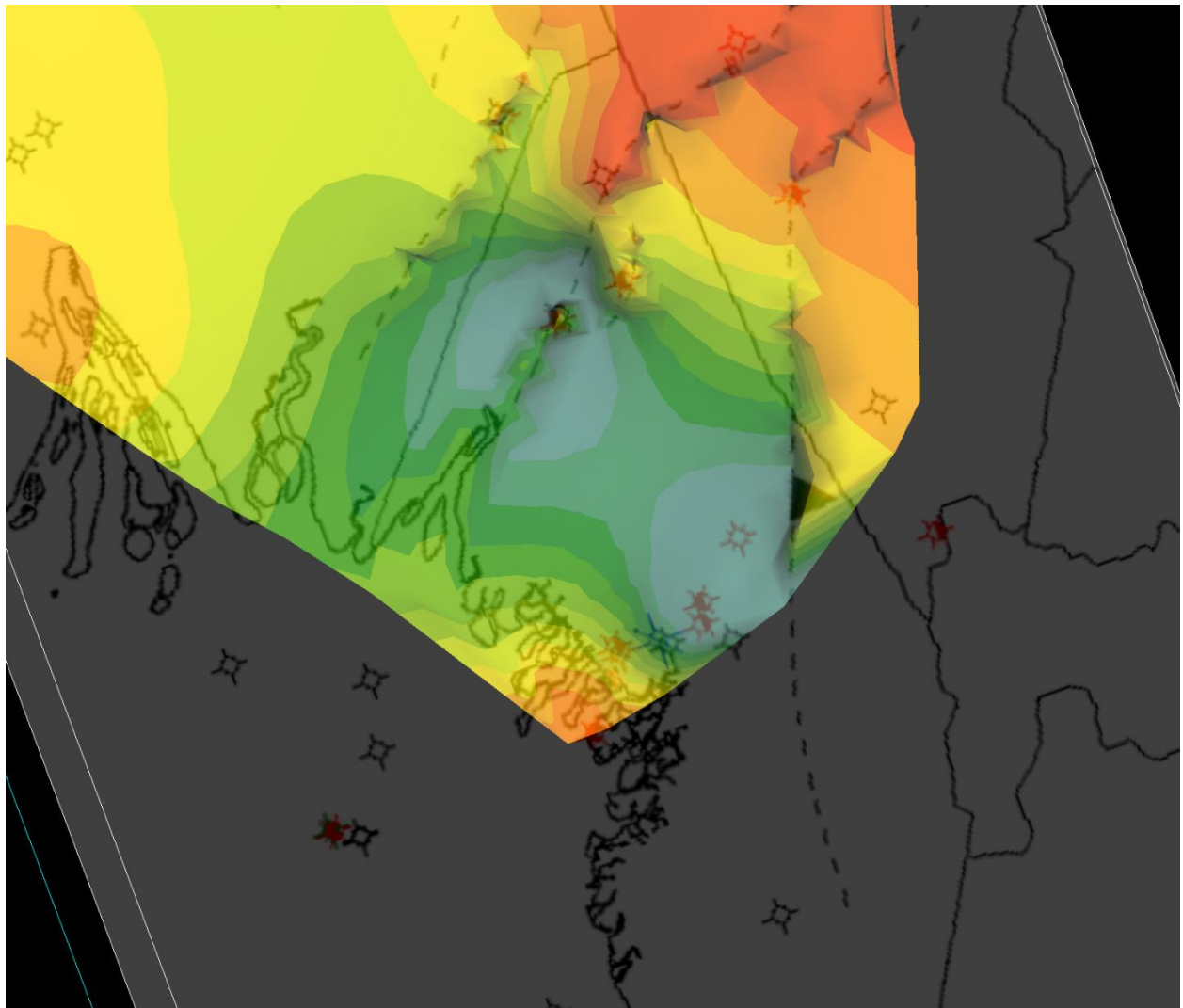
Appendix D

Additional 3D Modeling of Jurassic units with borehole's shown.





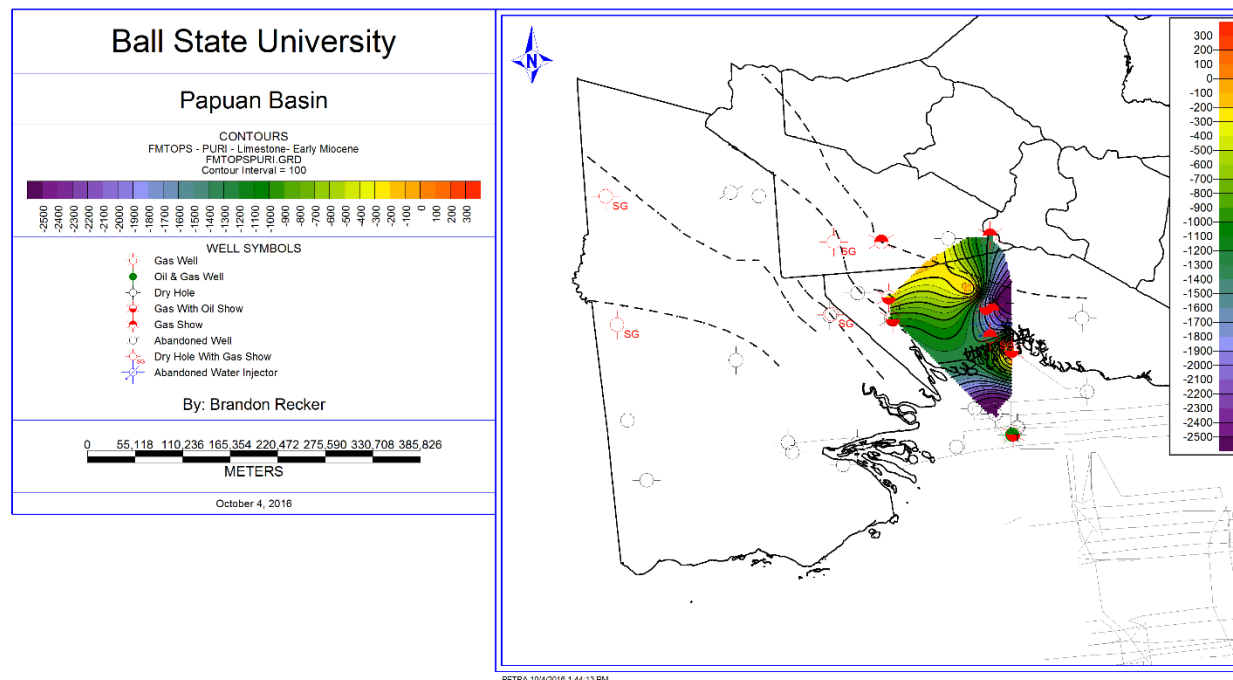
3D Ieru Formation with the Papuan Basin land overlay.



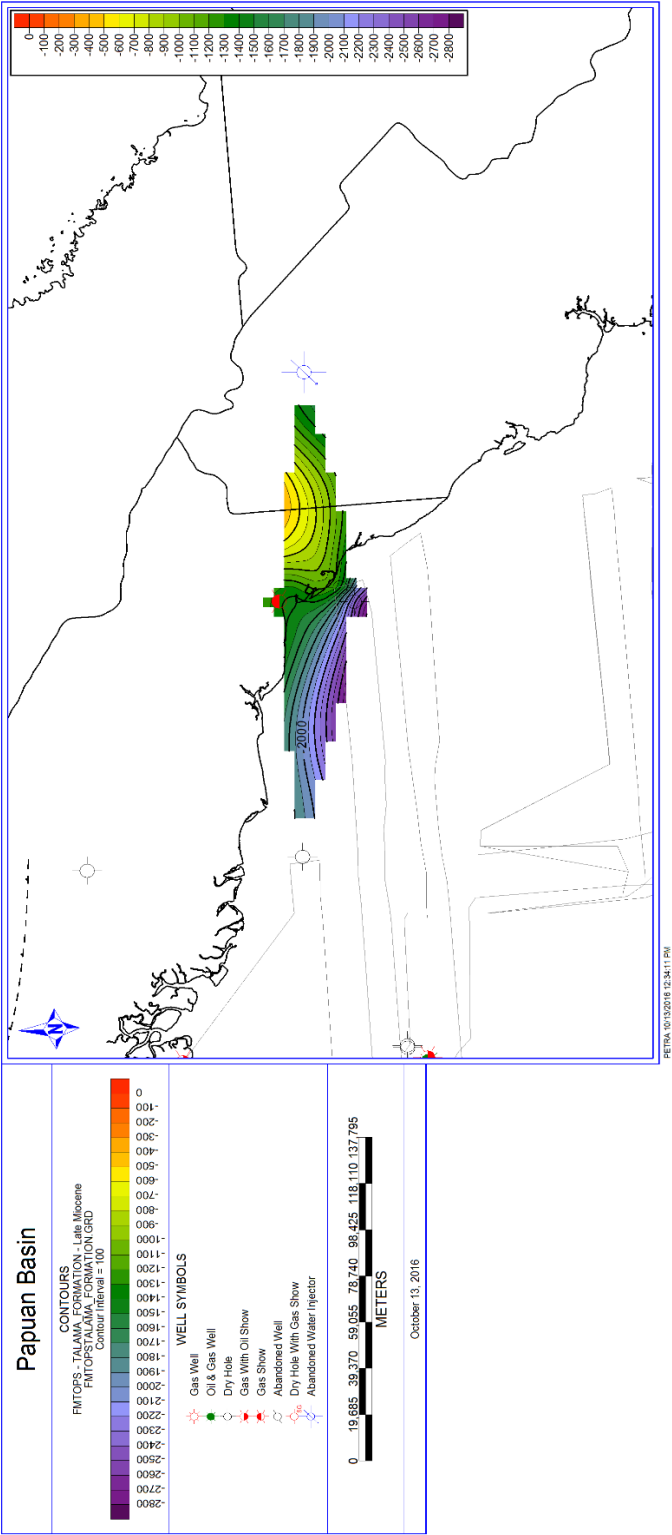
Appendix E

Contoured grid maps of additional Formations in the Papuan Basin.

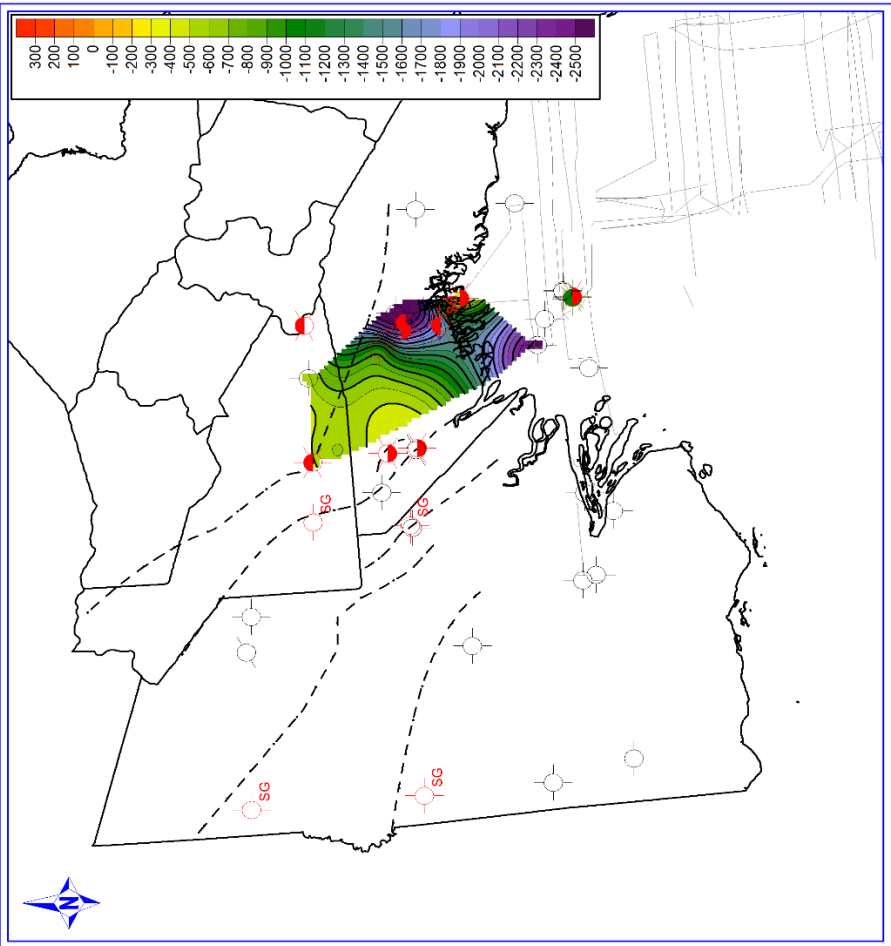
Puri Limestone – Early Miocene



Talama- Late Miocene



Yala- Late Miocene



PETRA 10/4/2016 1:39:55 PM

Ball State University

Papuan Basin

CONTOURS
FMTOPS - YALA - Limestone-Late Miocene
FMTOPSYALA.GRD
Contour Interval = 100

WELL SYMBOLS

- Gas Well
- Oil & Gas Well
- Dry Hole
- Gas With Oil Show
- Gas Show
- Abandoned Well
- Dry Hole With Gas Show
- Abandoned Water Injector

By: Brandon Recker

0 55.118 110.236 165.354 220.472 275.590 330.708 385.826
METERS

October 4, 2016